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Acoustic Positioning for Space Processing Experiments

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Final Report

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Prepared for:

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ABSTRACT

An acoustic positioning system is described that is adaptable to a range of processing chambers and furnace systems. Operation at temperatures exceeding 1000°C is demonstrated in experiments involving the levitation of liquid and solid glass materials up to several ounces in weight. The system consists of a single source of sound that is beamed at a reflecting surface placed a distance away. Stable levitation is achieved at a succession of discrete energy minima contained throughout the volume between the reflector and the sound source. Several specimens can be handled at one time. Metal discs up to 3 inches in diameter can be levitated, solid spheres of dense material up to 0.75 inches diameter, and liquids can be freely suspended in 1-g in the form of near-spherical droplets up to 0.25 inch diameter, or flattened liquid discs up to 0.6 inches diameter. Larger specimens may be handled by increasing the size of the sound source or by reducing the sound frequency. Shaping of the freely suspended liquid drops is accomplished by adjusting the sound pressure. The system appears free of significant instabilities - constraining forces on the specimen are measured to be about 15% of the force needed to overcome gravity. Electrical power for terrestrial position control is about 100 to 150 watts. Chamber dimensions may be of the order of several inches to several feet. Capillary injection methods are described for introducing liquid materials into the position control system, forming critical size droplets without significant material loss. Solid specimens are injected by acoustic lift-off of the specimen from a fine wire mesh screen placed close to the desired levitation point (energy well); the wire mesh screen is substantially transparent to the sound. Powder specimens are injected by acoustic lift-off of the powder from a wire screen - the sound field agglomerates the powder into a powder ball that positions itself within the nearest energy well. Experimental results are presented for the supercooling of organic materials and for water. Benzophenone is shown to be supercooled by 10% of the melting point temperature. Estimates are presented on the increase in nucleation rate caused by the sound field. Drop tower equipment and a high/low temperature acoustic levitator is fully readied for drop tests. The drop tower equipment is complete and is described in this report.

ACOUSTIC FIELD POSITIONING FOR CONTAINERLESS PROCESSING

FINAL REPORT

NASA Contract No. NAS8-30471

SUMMARY REPORT

The non-contact positioning of materials in a space processing chamber is accomplished using a new type of acoustic levitator. Liquid and solid materials are positioned using a single source of sound. Fine control of position may be obtained by motion of an acoustical reflector. Electrical power required is usually less than 100 watts. The system operates satisfactorily at high and low temperatures and is adaptable as an "add-on" feature to existing space experiments. Containerless melting and solidification can be performed and a freely suspended liquid can be shaped to the contour of the sound field. Experiments are described in which aluminum, glass and plastic materials are melted and solidified in the containerless state. The system has applications to containerless crystal growth, melting and related processes. Considerable advances in the utility of the system would result using thermal imaging techniques for heating the specimens. Also, for the research rocket considerable advantages would obtain using the transparent furnace; i.e., a quartz furnace embodying a gold plated heat reflecting surface.

TECHNICAL REPORT

1. Introduction

Manufacturing processes undertaken in an orbital space station may be seriously effected by drift of the material being processed. Control of the position of the material is generally desirable. The objective of this paper is to describe a new type of acoustic position control system that can be adapted to existing space processing chambers with minimum modifications to the chambers. The acoustic system to be described departs from existing systems in that only one sound source is used. The single sound source is used to excite the chamber volume into normal modes of vibration. Whenever there is a region in the experiment chamber at which the acoustic potential energy is a minimum, the specimen will be urged towards this region and remain freely suspended, if the acoustic forces are strong enough. Liquid and solid materials can be freely suspended by this method, up to several ounces in weight under 1-g. The shapes of the levitated materials can be spherical or disc-shaped. The spherical bodies are limited in size to about one half wavelength of sound (1.7 cm diameter for a 10kHz levitator). Flat blanks of material

can be considerably larger than the half wavelength criterion and still remain stably levitated. Specimens can, under certain conditions, be spun on an axis for degassing purposes, without touching the specimen. The shape of a liquid specimen can also be made to conform to the shape of the localized acoustic field. The system has been operated in a range of configurations of experiment chambers including rectangular and cylindrical experiments units.

Experiments have been conducted, and will be described later, in which the effect of the levitator sound field on a supercooled liquid has been determined. The indications are that the sound energy coupled into the specimen must exceed the cavitation threshold in the liquid. The cavitation threshold is several orders of magnitude larger than the sound levels that can reasonably be expected to be coupled into the specimens. The indications are that the levitator sound field will not disturb the material processes. This point is given greater credence when the levitator is operated under the low-g conditions pertinent to space processing. The acoustic field strengths can be reduced greatly and thereby further reduce the effects of these fields upon the material being processed.

Several position control systems for space manufacturing have already received study and development by other investigators. The triaxial system developed at the Jet Propulsion Laboratory utilizes three low frequency sound sources and relies upon the opposing action of the acoustic radiation pressure in three crossed sound beams for positioning the object. The electromagnetic position control system, a version of which has been developed at the General Electric Laboratories, utilizes three field coils. The electromagnetic system has the unique advantage of operating in a vacuum but is limited in use to electrically conducting materials.

Later sections of this report show the acoustic system readied for drop tower testing.

PRINCIPLE OF OPERATION

A simplified version of the levitator is shown in Figure 1. The sound source consists of a plane circular piston that radiates a beam of sound toward a parallel reflecting surface placed a distance $n\lambda/4$ away, where λ is the sound wavelength in the levitator atmosphere and n is any integer. A standing wave is established between the sound source and reflector as shown by the pressure profile Figure 2. A body introduced into the sound field will move towards planes of minimum potential energy, corresponding to the planes of minimum sound pressure drawn in Figure 2.

The levitated material is constrained in the sideways direction by the near field pressure of the sound source. Three typical near field pressure profiles are drawn in Figure 2 for successive planes normal to the axis of the levitator. These pressure profiles are obtained by the methods described in Reference 1 and are for a piston radiator 4 sound wavelengths in diameter corresponding to a sound source 7.5 cm diameter resonated in air at 20kHz. The positions of stable levitation correspond to the regions where the pressure is minimized in the combined standing wave field and the near field. These regions are indicated by the small circles in Figure 2. The near field pressure distribution is circularly symmetric about the levitator axis so that stable levitation is obtained anywhere in a series of successive circular zones spreading outward from the levitator axis, each levitation zone being parallel, and closely neighboring the minimum pressure planes.

For the levitator to operate satisfactorily, the material being levitated should not be so large as to overlap successive pressure minima. The diameter of a sphere, for example, should not exceed one half of a sound wavelength in the gas atmosphere, otherwise pressures will tend to cancel. The limiting sphere size for stable levitation in a 10kHz air-filled levitator at room temperature is 1.7 cm diameter. Flat blanks of material can be levitated larger than the sphere. A specimen blank will come to equilibrium with the plane of the blank parallel to, but displaced a small distance from a minimum pressure plane. The blank thickness (measured in a direction normal to the planes of minimum pressure) should not exceed the half wavelength limit alluded to earlier. However, the lateral dimensions may exceed a half wavelength and are limited by the radial distances between the pressure troughs in the near field. For example, a disc approximately 5.5 cm diameter could be levitated at the minimum pressure plane cc', Figure 2. This distance of 5.5 cm corresponds to the distance between the outer pressure troughs in the near field, at this plane. The estimates of maximum blank diameter are modified by the reflection of sound from the blank itself. The sound reflection from the blank will enhance the standing wave between the blank and the sound source but tend to smear the near field. The sideways restoring forces are reduced so that levitation of the blank may be less stable.

An acoustic standing wave is shown in Figure 3, measured along the axis of an experimental nucleation tube. The nucleation tube was 7.5 cm in diameter and 30 cm in length, driven at one end by a 7.4 cm diameter piston radiator oscillating at 20kHz.

The far end of the metal tube was closed by a close fitting circular reflector that could be moved precisely along the tube axis. The upper curve of Figure 3 shows the increase in sound pressure and the corresponding increase in the gradient of the sound pressure as the gas column is tuned by adjusting the position of the reflector. Maximum sound pressure amplitude is obtained when the separation distance between the source and the reflector is $n\lambda/4$. The completely untuned condition, separation equal to $n\lambda/2$, (the lower curve of Figure 3), results in a reduction in the sound pressure and hence in the levitation force. The reduced gradients of sound pressure in the untuned condition would result in a longer time to restore the levitated body. Plastic spheres inserted into the tuned and excited tube reached their equilibrium positions close to the planes of minimum pressure. The small open circles in the upper curve of Figure 3 show the observed levitation points.

The magnitude of the sound radiation force on a small sphere in a plane standing wave is given in Reference 2 by the equation:

$$F = \pi R^2 (kR) \rho V^2 \cdot f\left(\ldots \right) \qquad 1.$$

where

R = radius of sphere
k = $2\pi/\lambda$ for the gas atmosphere
ρ = density of the gas

v_0 = acoustic particle velocity

$f\left[\frac{\rho_b}{\rho}, \frac{c_b}{c}\right] = 5/6$ for solid or liquid bodies suspended in a gas

The minimum potential energy exists at the velocity antinodal planes as described in Reference 2 at which planes the sound pressure is a minimum.

A solid sphere 0.4 cm radius would experience a radiation force of approximately 1800 dynes when placed at a velocity antinode in a 20kHz plane standing wave, in which the radiated sound intensity of the source was 1w/cm^2 (150 db sound pressure level) and the standing wave gain was threefold. At this acoustic field strength, the 0.4 cm radius sphere could weigh approximately 1.8 grams and remain levitated on earth. This corresponds to a density of about 7 for the sphere. Since higher sound intensities are available, the dense elements evidently can be levitated terrestially, if desired.

Sound absorption in the levitator gas reduces the distance at which a body can be levitated. For example, the pressure troughs in the standing wave shown in Figure 3 are considerably less pronounced as one moves away from the sound source.

The absorption of a low intensity plane harmonic sound wave is given in References 2 and 3 by the equation:

$$I = I_0 \, \varepsilon^{-\alpha x} \qquad 2.$$

where

I is the sound intensity

x is the distance measured in a direction normal to the wavefront

α is the attenuation constant

The attenuation constant is given by the equation:

$$\alpha = \frac{\omega^3}{2\rho c^3}\left[\frac{4}{3}\eta + \eta' + \chi\left(\frac{1}{c_v} - \frac{1}{c_p}\right)\right] \qquad 3.$$

where

ω is the regular frequency

η is the shear viscosity coefficient of the gas

η' is the compressional viscosity coefficient

ρ is the density of the medium

c is the velocity of sound

$\left.\begin{matrix} c_v \\ c_p \end{matrix}\right\}$ specific heats

It is seen that the attenuation coefficient varies as the square of the wave frequency. Thus, operation of the levitator at the lower ultrasonic frequencies results in a greater distance at which the object can be levitated. Also, the absorption given by equation 2 holds only for distances close to the source as mentioned in Reference 2, p 30. At greater distances than one wavelength from the source the absorption is considerably greater than that given by equation 2. The increase in absorption at the fundamental frequency depends upon the wave amplitude and may be an order of magnitude larger than that predicted by equation 2. The curves shown in Figure 3 can be used as a guide to indicate the absorption losses in a 20kHz levitator and the absorption in lower frequency systems can be scaled from these curves.

ACOUSTIC CAVITY ENERGY WELL LEVITATOR

The levitator described in the preceding section represents a limited version of the more general energy well levitator in which resonances are developed throughout the entire three dimensions of the experiment chamber. In this sense, the experiment chamber is viewed as an acoustic cavity that can be excited in a range of high and low order modes - the normal modes of vibration. Typical acoustic cavities are represented by experimental furnace tubes or the interior volume of a muffle furnace, all of which volumes are adaptable directly to energy well levitation through normal mode excitation.

The normal modes of vibration of a rectangular enclosure are given by the following equations obtained from References 4 and 5:

$$p_{n_x, n_y, n_z} = \begin{matrix}\cos\\ \sin\end{matrix}\left(2\pi \frac{x}{\lambda_x}\right)\begin{matrix}\cos\\ \sin\end{matrix}\left(2\pi \frac{y}{\lambda_y}\right)\begin{matrix}\cos\\ \sin\end{matrix}\left(2\pi \frac{z}{\lambda_z}\right) \qquad 4.$$

$$f = \frac{c}{2}\left[\left(\frac{n_x}{\ell_x}\right)^2 + \left(\frac{n_y}{\ell_y}\right)^2 + \left(\frac{n_z}{\ell_z}\right)^2\right] \qquad 5.$$

$$n_x, n_y, n_z = 0, 1, 2, 3 \ldots$$

where

p = sound pressure
c = sound velocity in the gas
λ = sound wavelength

A rectangular cavity is shown in Figure 4 excited in normal mode N_{223}. The dimensions of the cavity are ℓ_x = 8 cms, ℓ_y = 8 cms with $n_x = 2$, $n_y = 2$ and $n_z = 8$. For an acoustical signal of frequency 20kHz, injected into the chamber, the distance ℓ_z is calculated to be 7 cms, obtained from equation 5. These dimensions may be typical of a small space processing chamber.

The normal mode corresponding to any particular set of values of n_x, n_y and n_z can be produced by starting a plane sound wave in the direction given by the direction cosines [illegible] and letting the wave reflect until it becomes a standing wave. Thus, the sound generator used to produce levitation in a cavity experiment chamber should be inserted at an angle given by the direction cosines. If this is not effected, the resultant wave in the experiment chamber will not be periodic and will not correspond to a normal mode (See Reference 4, p.390).

The sound pressure isobars for the cavity shown in Figure 4, are plotted in Figure 5 for the X-Y plane at Z = 0. Note that there are four pressure minima and consequently four levitation points in the X-Y plane at Z = 0.

The isobars shown in Figure 5 are repeated periodically as one moves along the Z axis. Since there are 8 half wavelengths in the Z direction ($n_z = 8$), there are consequently 32 distinct levitation regions in the cavity. However, the depth of each energy trough will be governed by the absorption of sound. The energy troughs near to the sound source will be stronger than those a distance away.

Various examples of acoustic cavity levitators are given in the next section.

APPARATUS

The sound source used throughout the investigations is shown in the photograph Figure 6. The source consists of a cylinder of magnesium-aluminum alloy about 7.5 cm in diameter and of length equal to a one half sound wavelength in the alloy. The vibrator is supported by a flange at the midsection - a displacement node - and excitation of the vibrator is provided by inducing eddy currents in a metal tube turned integrally with the base of the vibrator. A full description of an early version of this vibrator is given in Reference 1.

A muffle furnace shown in Figure 7 is adapted for use with the sound source. This is accomplished by removing a firebrick from the underside of the furnace and placing the front end of the sound source so that it is centered in the firebrick hole, pointing vertically upwards. A fixed

reflector, consisting of a flat slab of stainless steel is supported within the furnace at a distance equal to 4 half wavelengths of sound from the vibrator surface and parallel to it. To reduce heating of the vibrator by the furnace heat, a series of parallel, 200 mesh, stainless steel wire mesh screens are placed immediately above the vibrator in a plane parallel to the vibrator surface. The wire mesh screens introduce very small absorption of the sound wave, but effectively conduct away the heat that otherwise might impair the performance of the vibrator. A detailed description of acoustical transmission through wire mesh screens is given in Reference 6.

An experimental furnace module, suitable for drop tower and rocket experiments, is shown in Figure 8, equipped with the acoustic levitator, for levitating specimens of chalcogenide glass. The furnace operates at 800°C, at which temperature solid specimens can be levitated and melted. The furnace module consists of a fused quartz tube measuring 7.5 cm diameter by 15 cms in length, outside of which are placed two nickel-chromium heating elements. The top end of the quartz tube is closed by a refractory cap through which an inert gas can be passed by means of an inlet tube. An adjustable metal reflector is provided inside the quartz tube to increase the levitation forces.

PERFORMANCE EVALUATION

The stability of the acoustic energy well levitation process can be gaged from the three photographs shown in Figure 9. The upper photograph shows the levitator (frequency 20kHz) mounted inside a drop tower cage and pointing vertically upwards. A specimen can be seen levitated approximately halfway between the upper surface of the vibrator and the reflector. The center photograph in Figure 9 shows the specimen remaining levitated when the entire assembly is rotated through 90°. The lower photograph shows the system pointing vertically downwards. The system is stable and independent of the direction of the sound beam. We thus conclude that the energy wells are closed. In the center photograph of Figure 9, the levitated specimen is shown pulled by gravity to a position slightly below the position originally occupied in the upper photograph. The deflection of the specimen provides the means to measure the "sideways" restoring forces in the levitator. In the instance cited, the lateral restoring forces are about 10% of the levitation forces in the direction of the main sound beam.

The photographs shown in Figures 10 and 11 demonstrate levitation of liquid and solid materials. The levitator frequency was 20kHz and the electrical power input into the vibrator was approximately 85 watts throughout. The left photograph in Figure 10 shows a levitated water droplet measuring approximately 0.4 cm in length. A considerable degree of flattening is observed. The flattening results from the sound radiation force. The droplet shape is governed by the surface tension of the water and the shape and strength

of the acoustic energy well in which it resides. By deliberately shaping the energy well, the liquid could, in principle, be formed to a desired shape without contacting surfaces. The right photograph in Figure 10 shows a solid aluminum sphere levitated, while the lower photograph in Figure 11 shows a levitated brass disc measuring about 5 cm diameter by 0.5 mm thick. Levitation of the disc is obtained without a separate reflector since the disc acts as its own reflector. Here, gravity is needed to retain the specimen in position. For space applications, a separate reflector would be required. The upper photograph in Figure 11 shows five spheres simultaneously levitated in the standing wave as indicated in Figure 3.

Position control in the levitator is effected by simply moving either the reflector or the sound generator. The specimen will follow the motion of the surface that is moved.

Acoustic "lift-off" of a specimen from a wire mesh screen is shown in Figure 12. The specimen will lift from the position of the spoon in the lower photograph to the position of the specimen in the upper photo.

APPLICATIONS

Free Suspension Melting

Low temperature containerless melting is demonstrated in the sequence of photographs in Figure 13. A picoelastic material, melting point 80°C, is introduced in the levitator and is shown in the top left-hand photograph. Partial melting of the material, obtained by means of a quartz lamp, is shown in the top right-hand photograph. It is observed that the material has taken an approximately spherical form. As the viscosity of the material reduces with increasing temperature, the sphere flattens (lower left-hand photograph) and finally the material is compressed by the sound vibration forces to a flattened disc-like shape. The spherical form could be retained by reducing the intensity of the sound field. In low gravity, for example, the sound fields could be reduced in proportion to the reduction in the gravity field. Consequently, little distortion of a spherical body should result from the acoustic levitation. A penalty, however, is the increasing time to restore the body to equilibrium, when the sound fields are reduced.

High temperature containerless melting of aluminum and glass is shown in Figures 14 and 15, respectively, undertaken in the muffle furnace levitator described in the previous section. The top photograph in Figure 14 shows an irregular, solid, aluminum ball, introduced into the furnace. The sound vibrator is directed upwards through the bottom of the furnace as described previously. The flat plate, situated midway between the bottom and top of the furnace, is the reflector. Furnace temperature, measured at a distance of 7 cms to the rear of the specimen, was 1000°C. After an elapsed time of 40 seconds a photograph was taken, shown at the bottom of Figure 14. At this point, the aluminum had melted and was approximately spherical in form.

Figure 15 shows two photographs of containerless glass melting. Each photograph was taken 30 seconds apart. In the top photograph a glass disc, 1 cm in diameter, was inserted into the furnace and levitated. The disc is situated towards the top right-hand side of the picture. The bottom photograph shows the glass disc melted to form a sphere of molten glass that remained stably levitated. The furnace temperature was 800°C for this sequence of photographs. Electrical power into the levitator was 200 watts. Small random motions of the levitated sphere were observed. Those random motions were mostly caused by drafts entering the open front door of the furnace.

Liquid Injection

Injection of liquids into the levitator may present a problem if the liquid is not injected into an energy well and if too much liquid is inserted at any one time. Improper liquid injection results in break-up of the liquid droplet and consequent fouling of the experiment chamber. A method of liquid injection consists of detaching the droplet from the end of a capillary tube. The weight of the largest drop that can hang from the end of a tube of radius a, is $mg = 2\pi a \gamma \cos \alpha$ where γ is the surface tension and α is the angle of contact with the tube. By choosing a tube of diameter calculated from this equation the size of the drop can be obtained, that the levitator will accept without liquid break-up. This is demonstrated by the two photographs shown in Figure 16. The top photograph shows a water droplet growing at the end of a capillary tube that is inserted into the levitator. As the drop grows, it will tend to move in the sound field, but remain attached to the capillary tube. The capillary tube is now moved until an energy well is found where the droplet reaches equilibrium and shows no tendency to oscillate. After a few seconds the droplet will detach when it reaches critical [illegible] and remain levitated. The detached droplet is shown in the bottom photograph in Figure 15. Under low gravity a slight gas overpressure in the capillary tube should suffice to eject the liquid from the capillary tube.

Liquid Shaping

Levitated liquids may be shaped by increasing or decreasing the sound pressure or, alternatively, by shaping the acoustic energy well in which the levitation takes place. A sequence of photographs of a levitated water drop is shown in Figure 17. The photographs were each taken at a different sound pressure level. It can be seen that the drop progressively flattens as the sound pressure is increased.

EFFECT OF THE LEVITATOR SOUND FIELDS ON THE PROCESSING OF MATERIALS

A series of experiments was conducted to indicate the effect, if any, of the levitator sound field on the material being processed. From the

viewpoint of classical acoustics, the mismatch in acoustical impedance between the levitator gas in which the sound field propagates and the material levitated, is considerable, and the energy transfer should be extremely small. For example, the acoustical impedance of air is 42 cgs units and that of water 1.5×10^5 cgs units. The impedance mismatch is about 3500 to 1 resulting in an energy transfer ratio equal to the square of this ratio, or about 1.2×10^7 to 1. However, other disturbances could arise in a levitated material such as surface or volume resonances that may increase the energy transfer from the sound field.

To check the sensitivity of a material process to the levitator sound field, the following experiments were conducted. A droplet of benzophenone (M.P. 47°C), measuring 4 mm diameter, was levitated and allowed to supercool in the levitator while freely suspended. It was observed that the droplet supercooled by 15% of the melting point temperature without any indication of crystallization. During the cooling process the drop was viewed continuously under a microscope using a polarized light source to indicate any tendency of the liquid to solidify.

In the second experiment, it was decided to irradiate a supercooled liquid by coupling sound into the liquid by direct immersion of an ultrasonic transducer. The acoustic energy transfer is high, in this condition, such that 50 to 60% of the sound energy generated in the transducer is propagated into the liquid. The experimental apparatus is shown in the top photograph of Figure 18. The metal cylindrical stub of the acoustic transducer can be seen immersed in the liquid (benzophenone) in the foreground of the photograph. At the bottom right side a small acoustic probe can be seen which is used to detect the sound field. This probe is connected to a narrow band electrical filter that can be switched into the circuit and used to suppress the direct acoustic signal received from the transducer. The liquid was supercooled, as shown by the bottom curve of the supercooling curves plotted in Figure 19. At a temperature of 30.8°C the transducer was excited at the increasing voltages labelled on the curve. At a transducer drive voltage of 220 volts, acoustic cavitation was visually observed in the liquid benzophenone, whereupon the liquid crystallized at a high rate, shown by a sharp increase in temperature of the liquid - the lower curve in Figure 19 - and shown by the crystallization evident in the photographs in Figure 18. Just prior to the inception of crystallization, the acoustic probe indicated a noise signature shown by the oscilloscope traces in the photographs. The noise signature was characteristic of sonic cavitation (See References 1, 7 to 11). Prior to the inception of cavitation the acoustic intensity in the liquid was substantial, and from the acoustic probe reading, was calculated to exceed 0.1 watt/cm^2. At the 0.1 watt/m^2 acoustic radiation level, no effect on the crystallization process could be observed as shown in Figure 18. The evidence appears to indicate that the sound fields must reach the cavitation level for these fields to effect crystallization of the material. An exception would be in a specific instance in which a deliberate attempt was made to couple the gas-born sound

energy to the material, for purposes of acoustic mixing of the material, homogenization or other acoustic processing factors. In this event, the sound frequency could be adjusted to resonate the material and increase the energy coupling. These factors considered further in the Appendix.

DROP TOWER APPARATUS

Two configurations of equipment have been set-up, ready for drop tower testing. The first system is designed exclusively for use at room temperature. The system is that shown variously in figures 9 and 12. The second system fabricated is for use at high temperatures - temperaturs to 1000°C. This high temperature system is shown in Figure 21. In this figure we show the basic furnace module (also suitable in its present form for the research rocket) that is mounted in the standard drop tower framework shown in figures 9 and 12, for the drop tower tests. Alternately, we have designed the higher temperature drop tower system to use a quartz tube furnace, electrical resistance heated as shown in figure 8. About 15 minutes preheating time is required to preheat the drop tower furnaces. The samples are positioned by means of wire mesh screens and lift-off of the specimen is obtained using the acoustic positioning applied just prior to the start of the drop. Sequencing of the camera is carried out using the standard drop tower cage equipment. We have fabricated a separate drop tower cage - one for the room temperature levels and one for the high temperature tests. In this way drop tower operating time is conserved.

CONCLUSIONS

The acoustic energy well levitator is capable of levitating and positioning liquids, and solid dense materials of sizes useful in space processing experiments. The method can be scaled to a full scale space manufacturing process. The virtue of simplicity is retained in the levitator, while operating in high temperature environments exceeding 1000°C. A gas atmosphere is necessary to conduct the sound, but the gas pressure can be reduced at the cost of reducing the levitation forces. Containerless shaping of materials can be accomplished, though precise shaping would require careful design of the experiment chamber to form the energy wells to the proper shape. Precise positioning can be obtained by moving a reflecting surface or by moving the sound source. By this means, a specimen can be translated from a hot region to a cold region. The energy well levitator is adaptable to a range of space experiments. Strip materials, flat blanks and discs are particularly easily handled.

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APPENDIX

Mechanisms Of Acoustic Cavitation And Effect On Crystallization

We have concluded earlier that cavitation levels of sound evidently are necessary to induce nucleation and crystallization of a supercooled liquid. We digress at this point to evaluate how these cavitation-related effects can occur and what their significance may be.

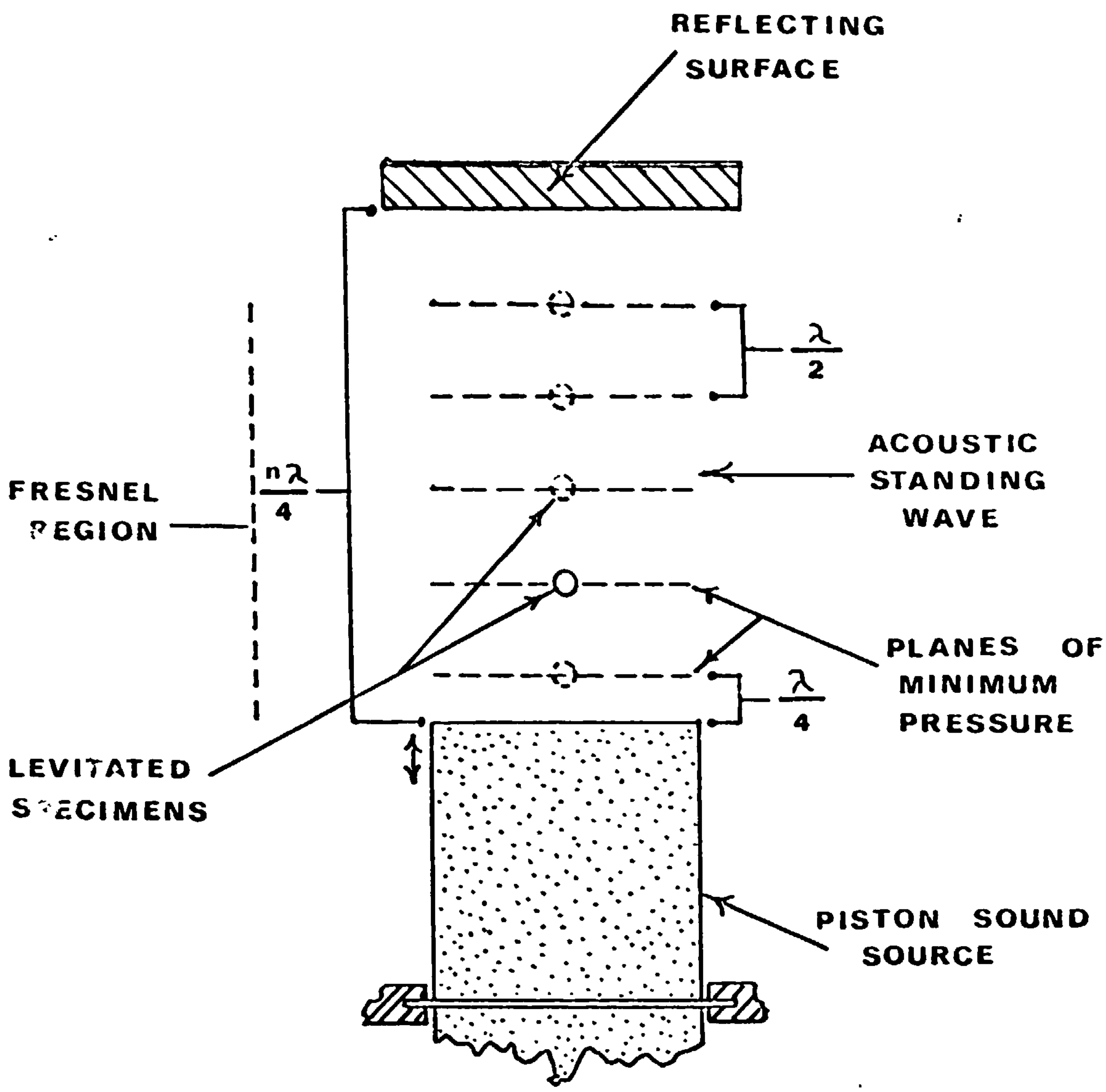
Cavitation processes start when a bubble or other nucleant enters a sound field. A bubble trapped in a sound field will begin to grow - a process known as rectified diffusion. If the localized sound intensity is low, the bubble will continue to oscillate. The bubble may grow to resonant size or coalesce with other bubbles and become visible to the naked eye. Gaseous cavitation such as this gives rise to a line spectrum of acoustic noise that may be measured with a broad band acoustic probe, as mentioned earlier. Pressure and particle velocities in the gaseous cavitation state do not much exceed those in the incident sound field. As such, gaseous cavitation generally is found to play only a minor role in changing the properties of liquids. This fact is brought out in a multiplicity of references of which References 7 to 11 have been selected. High sound intensities, usually of the order of 0.3W/cm^2 or greater give rise to vaporous cavitations. Vaporous cavitation arises as follows: Bubbles of a size such that their resonant frequency is higher than the incident sound frequency behave nonlinearly as shown in Reference 7. These bubbles grow at about the rectified diffusion growth rate, but at a critical size, the bubble collapses with extreme violence generating localized shock waves that further nucleate the liquid that surrounds the original void. Temperatures in the collapsing void may be extreme, and may exceed 10^4 degrees Kelvin. The acoustic noise shows a continuous spectrum and this spectrum can be used as a "label" for the existence of vaporous cavitation in a liquid. Vaporous cavitation is the principle mechanism whereby sound can induce fundamental changes in a liquid such as, for example, increasing the nucleation rates of a liquid.

The evidence from the photographs in Figure 18, showing the effect of direct sound irradiation of supercooled benzophenone, is reconsidered in the light of these considerations. The top left-hand photograph shows the condition with no sound radiation - the oscilloscope trace shows no vertical deflection indicating that no sound is being received at the acoustic probe.

The bottom left-hand photograph shows a small vertical trace produced by 0.1 W/cm^2 sound radiation at 20kHz of the liquid. This trace is found to be a noise signal consisting of a line spectrum and corresponds to the gaseous cavitation, as alluded to earlier. Vaporous cavitation is incepted very suddenly at a slightly higher sound level as seen visually in the top right-hand photograph taken 100 milliseconds later. The vaporous cavitation is identified by the streamers emanating from the bottom face of the transducer and moving in a curved path to the right of the picture. The oscilloscope trace shows the characteristic jump in the acoustic noise level due to the addition

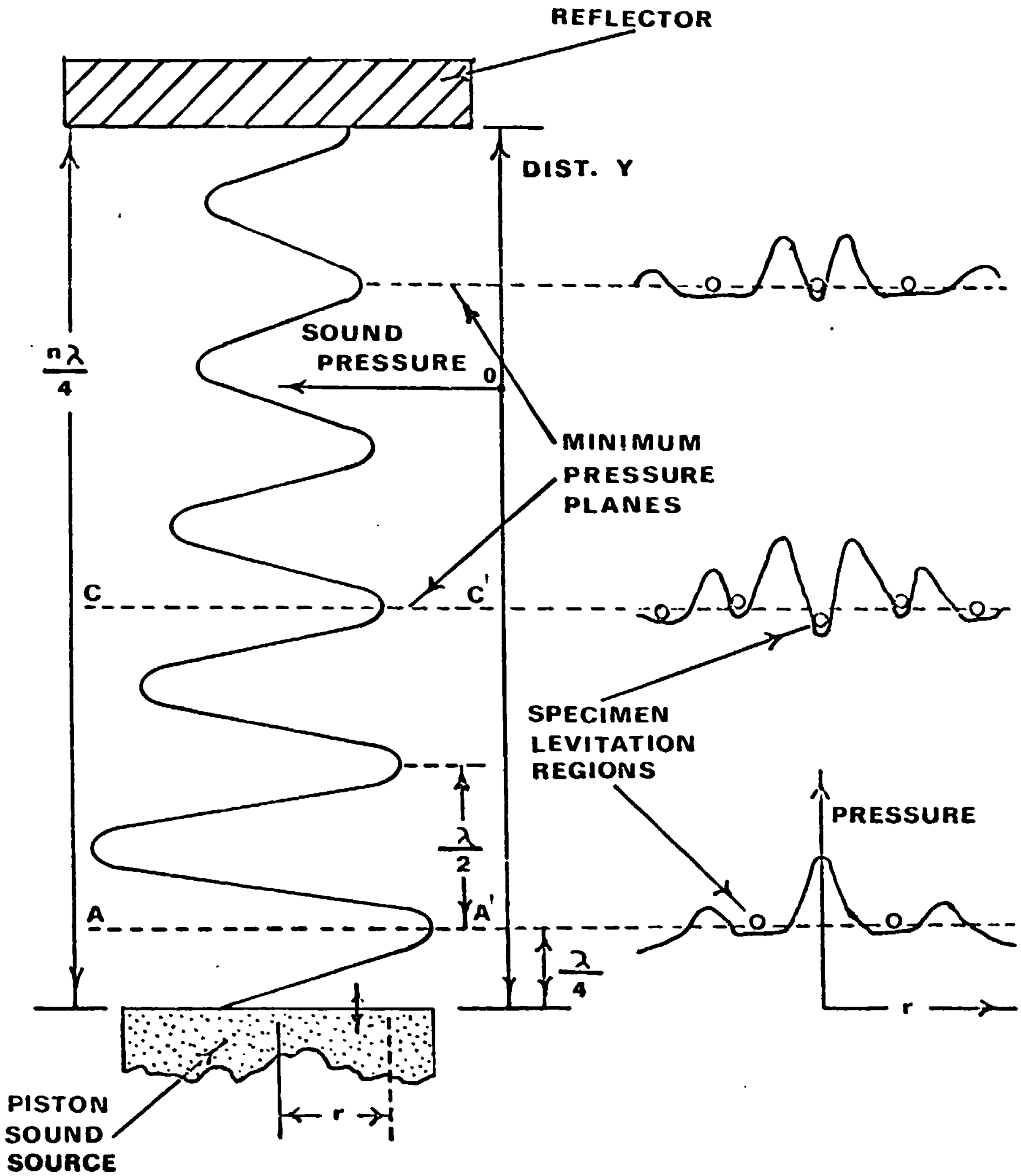
of the continuous noise - further identifying the existence of vaporous cavitation. Almost instantly with the start of vaporous cavitation, we have the start of nucleation and crystallization in the liquid as shown in the bottom right photograph. A few seconds after this picture was taken the whole container of supercooled benzophenone had solidified. Note that the oscilloscope trace has disappeared even though the sound remains on. This is because the crystals of benzophenone absorb the sound and prevent the sound from reaching the acoustic probe.

The evidence from this experiment is that the vaporous cavitation threshold must be exceeded for the sound to cause crystallization and nucleation of the material. As discussed earlier, it is very improbable that these levels of sound energy can be coupled from the levitator to a fully suspended liquid.



THE ENERGY WELL LEVITATOR

FIG. 1

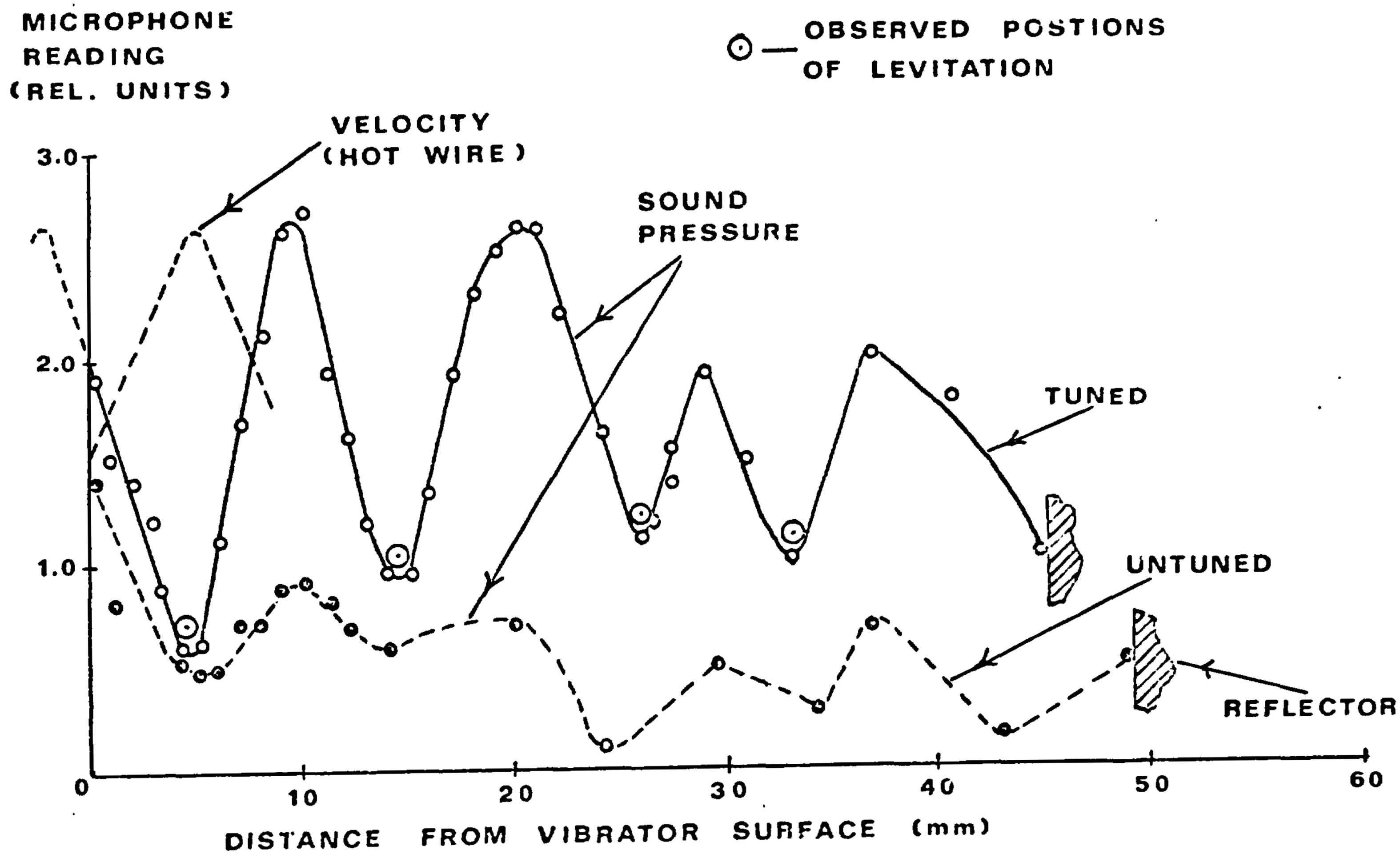


STANDING WAVE

NEAR FIELD

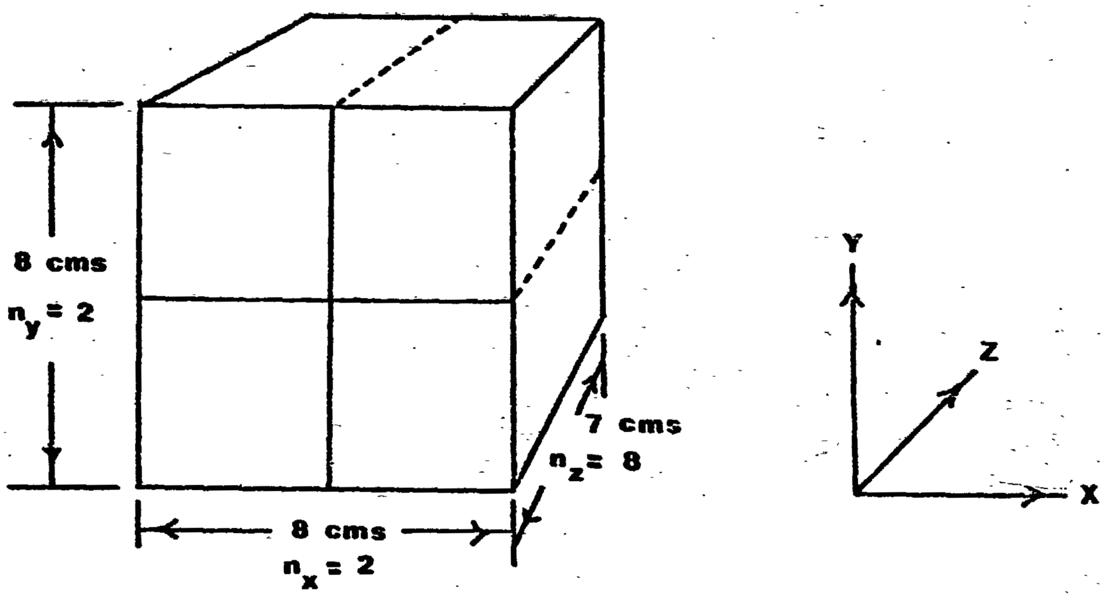
DISTRIBUTION OF SOUND PRESSURE

FIG. 2



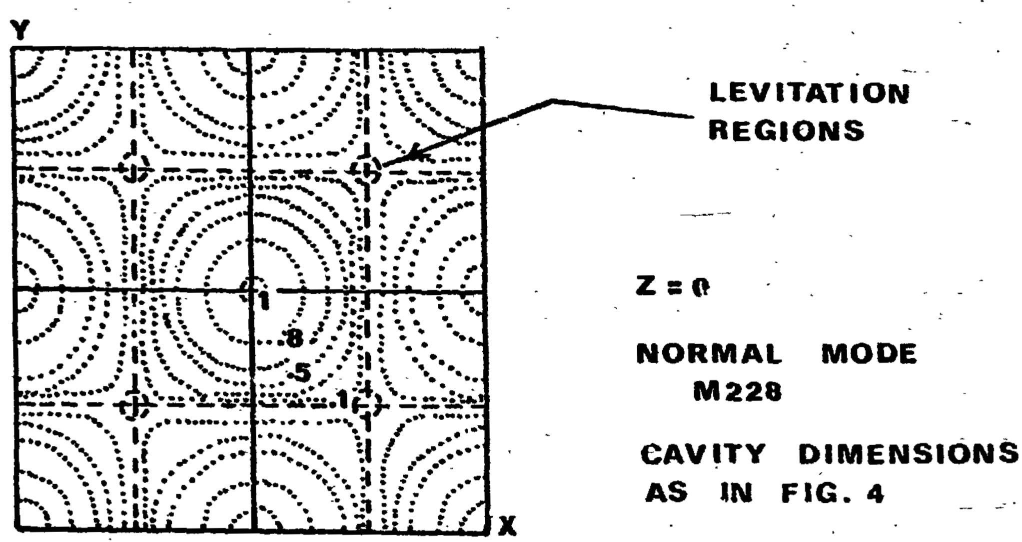
LEVITATOR STANDING WAVE

FIG. 3



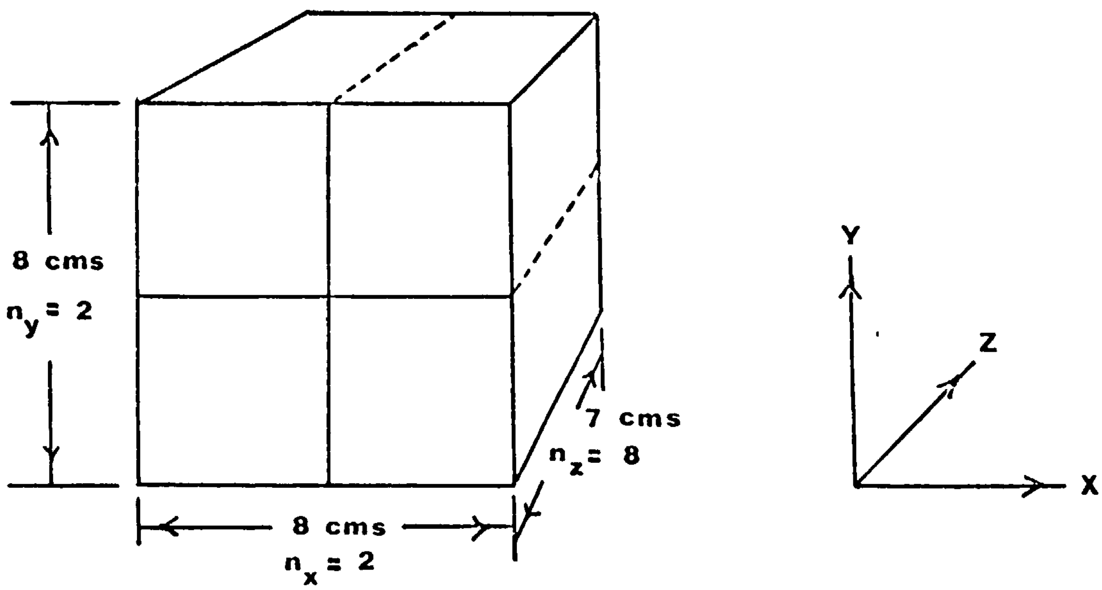
ACOUSTIC CAVITY LEVITATOR

FIG. 4



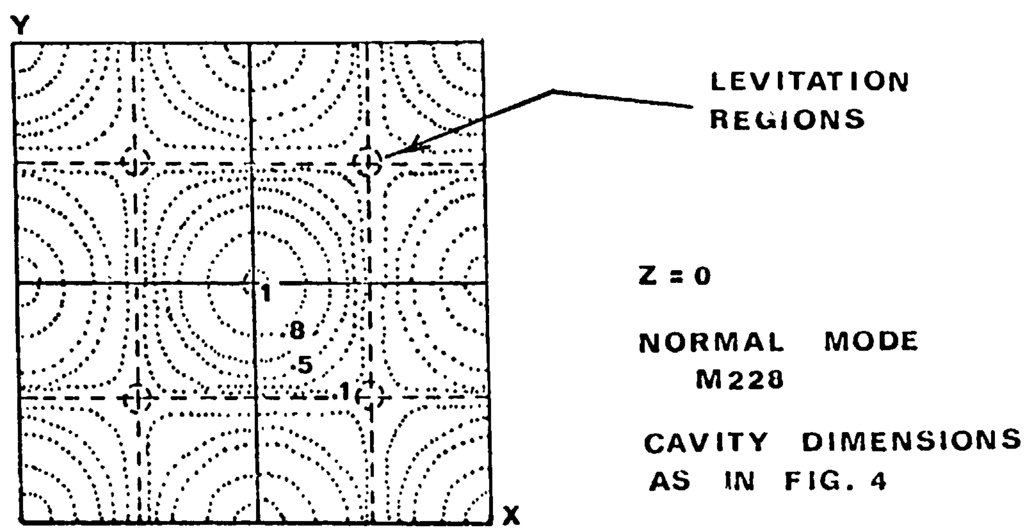
ISOBARS FOR A RECTANGULAR CAVITY

FIG. 5



ACOUSTIC CAVITY LEVITATOR

FIG. 4



ISOBARS FOR A RECTANGULAR CAVITY

FIG. 5

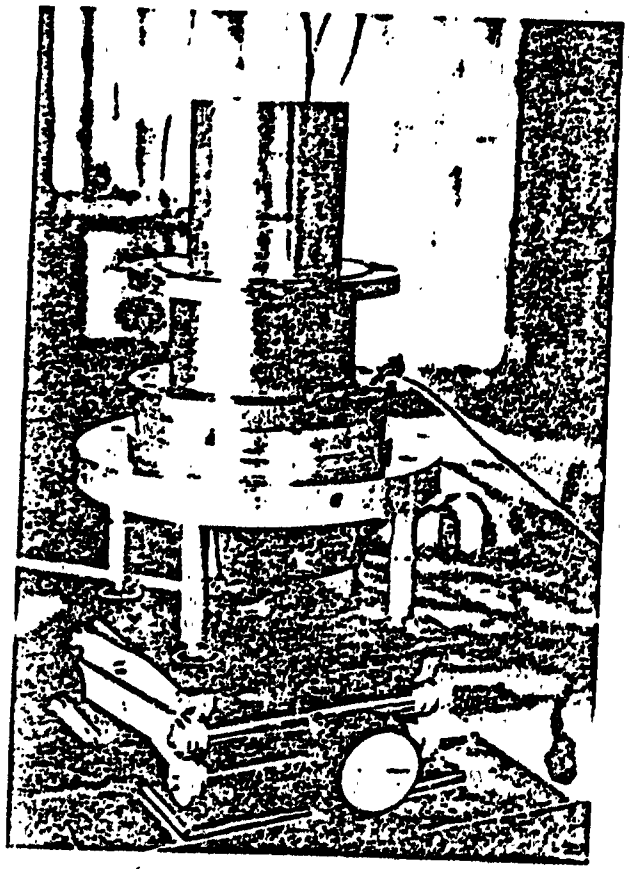


FIG. 6

Ultrasonic Intense
Sound Source

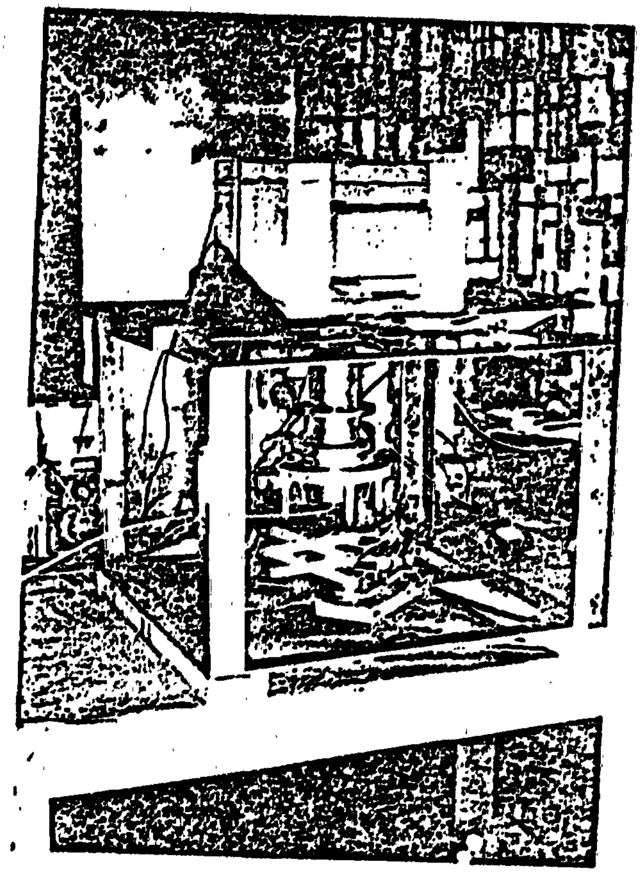


FIG 7

Sound Source Coupled
To Muffle Furnace

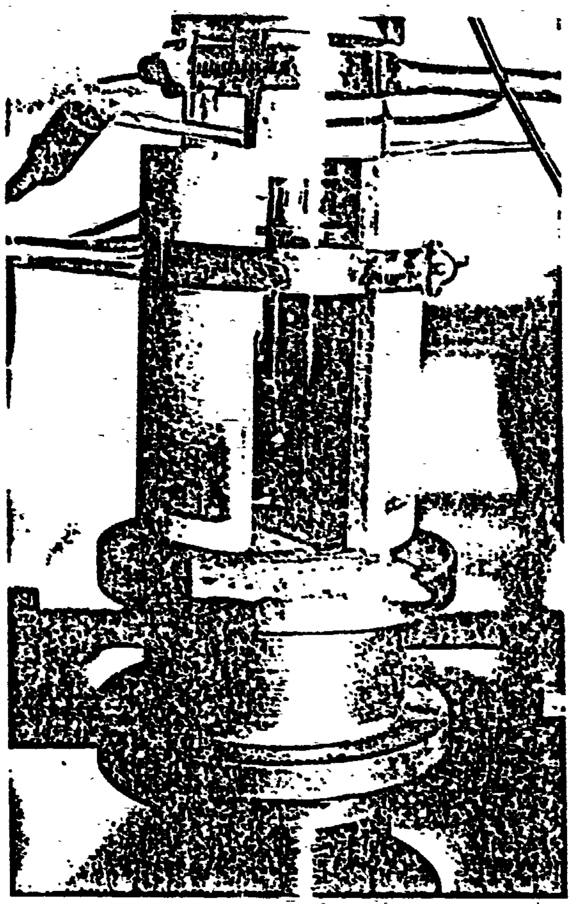


FIG. 8

Fused Quartz Furnace
For Containerless Melting

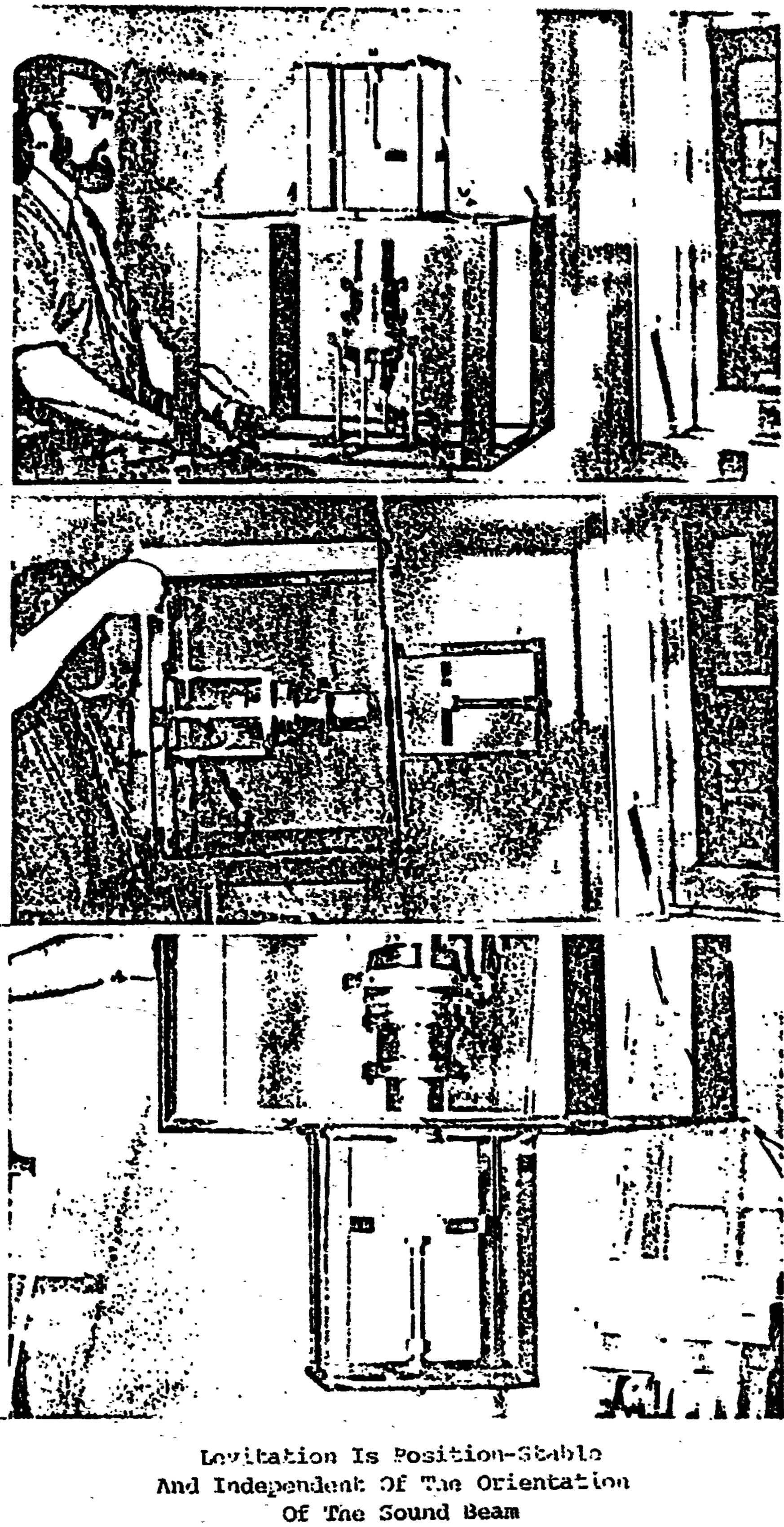


FIG. 9

Levitation Is Position-Stable
And Independent Of The Orientation
Of The Sound Beam

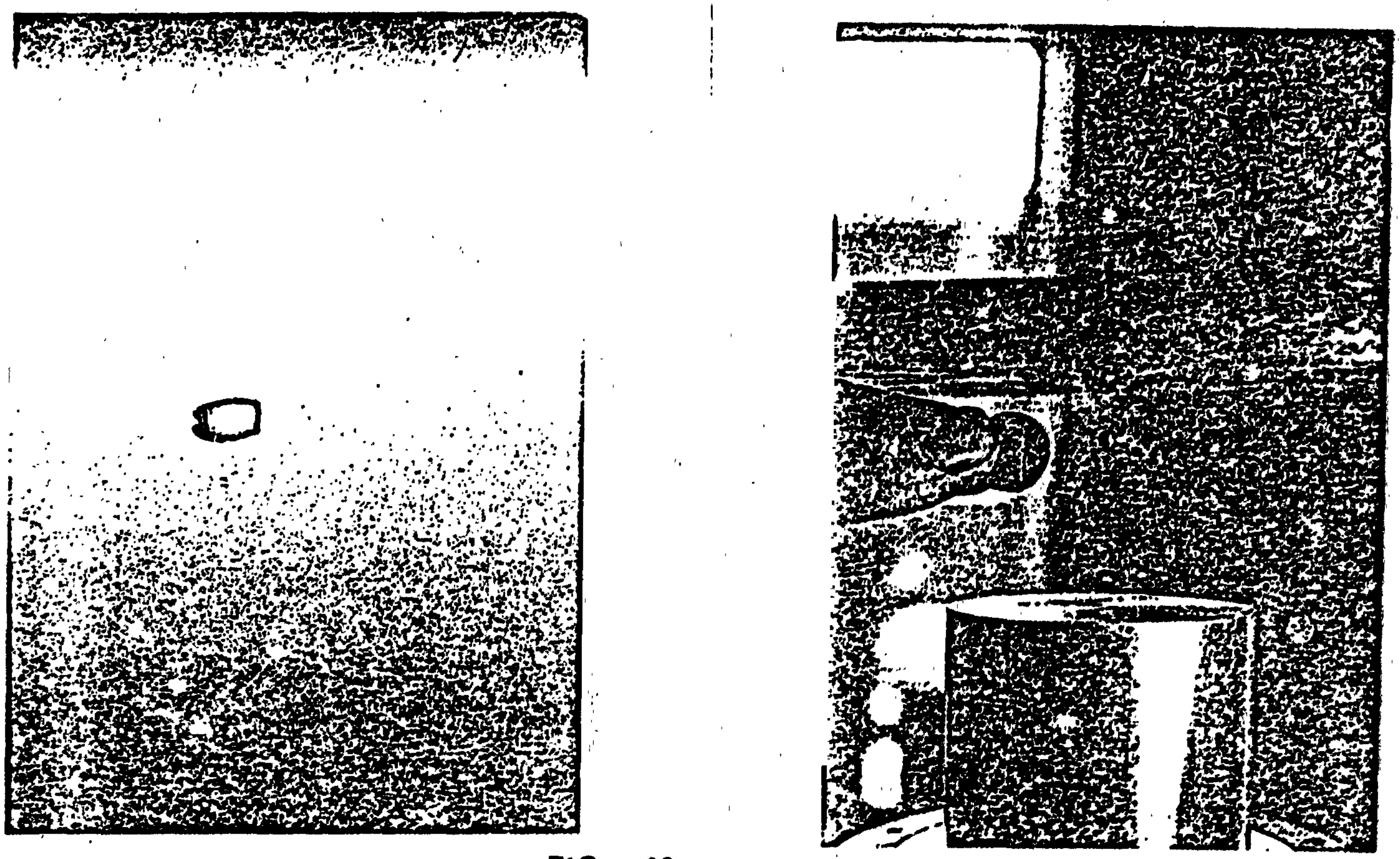


FIG. 10

Levitation Of A 3mm Water Drop
(Left-Hand Photo). Free Suspension
Of Solid 0.5 cm Diameter Aluminum Sphere
(Right-Hand Photo)

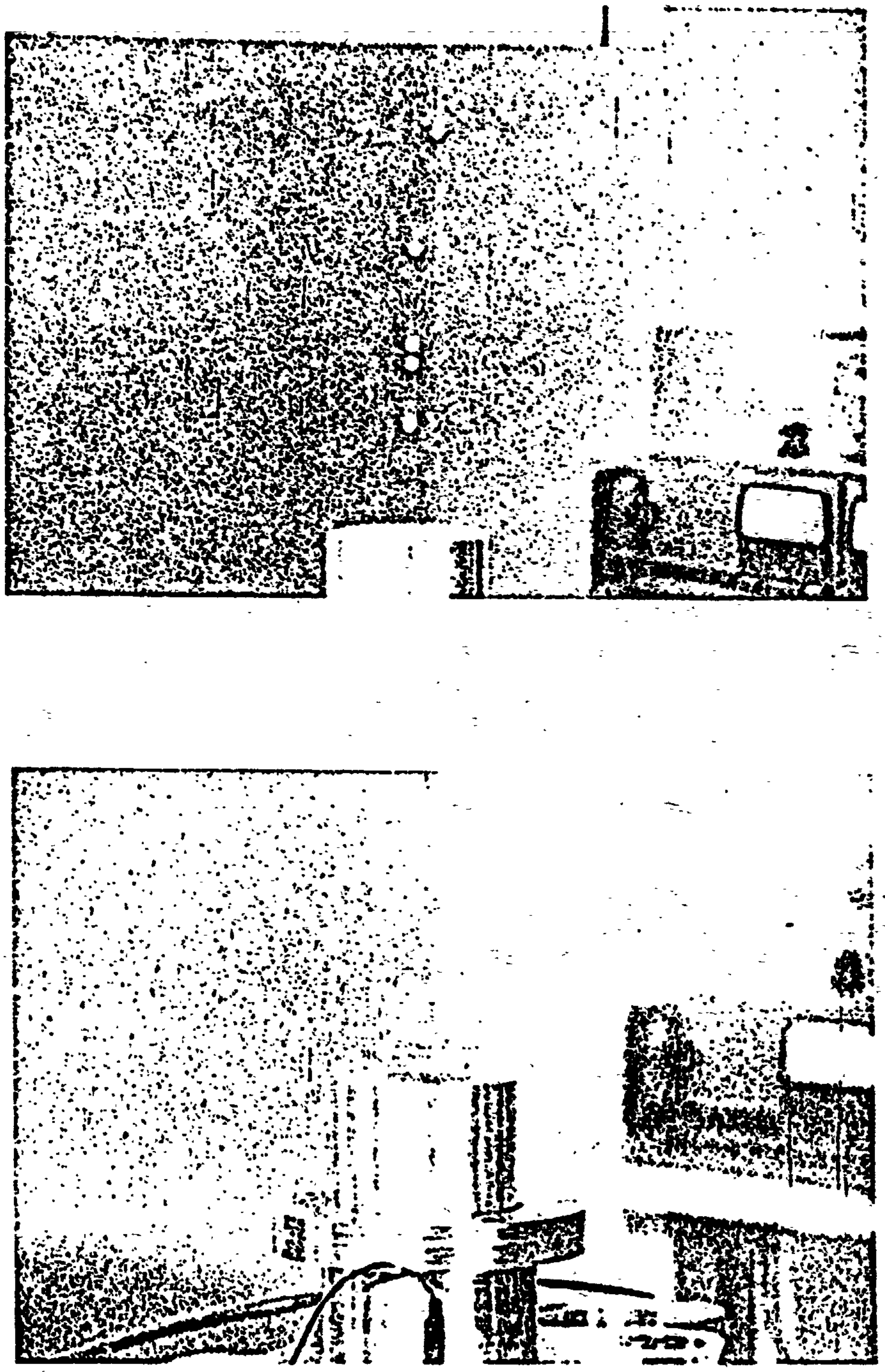


FIG. 11

Free Suspension Of A 7.0 cm Diameter
Brass Disc (Lower Photo).
Levitation Of Multiple Specimens In An
Acoustic Standing Wave (Upper Photo)

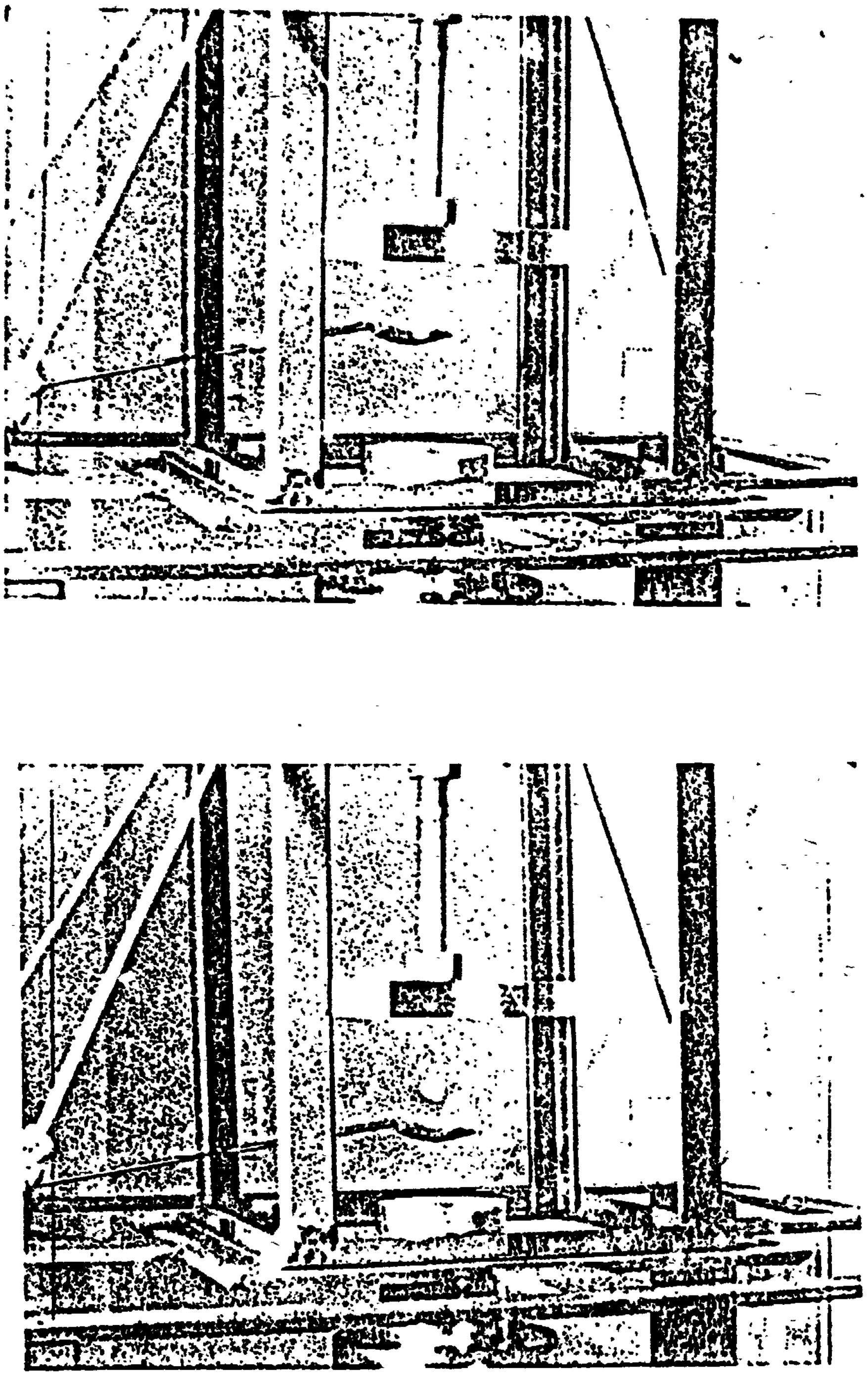


FIG. 12

Acoustic Lift-Off Of A Specimen
From A Wire Mesh Specimen Support

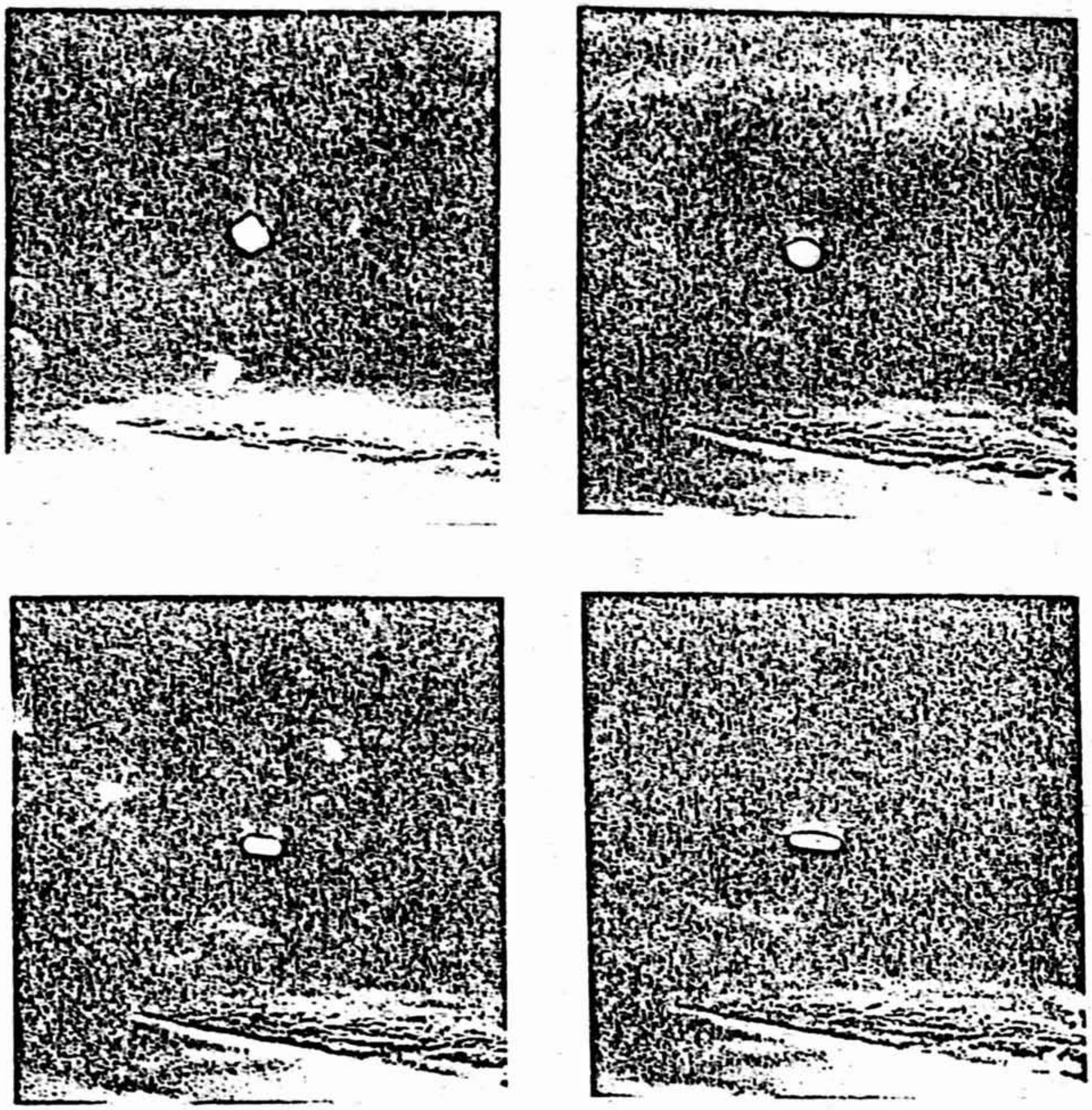


FIG. 13

Containerless Melting Sequence
For Viscoelastic Material. Photos Taken
At 4[illegible] Second Time Intervals.

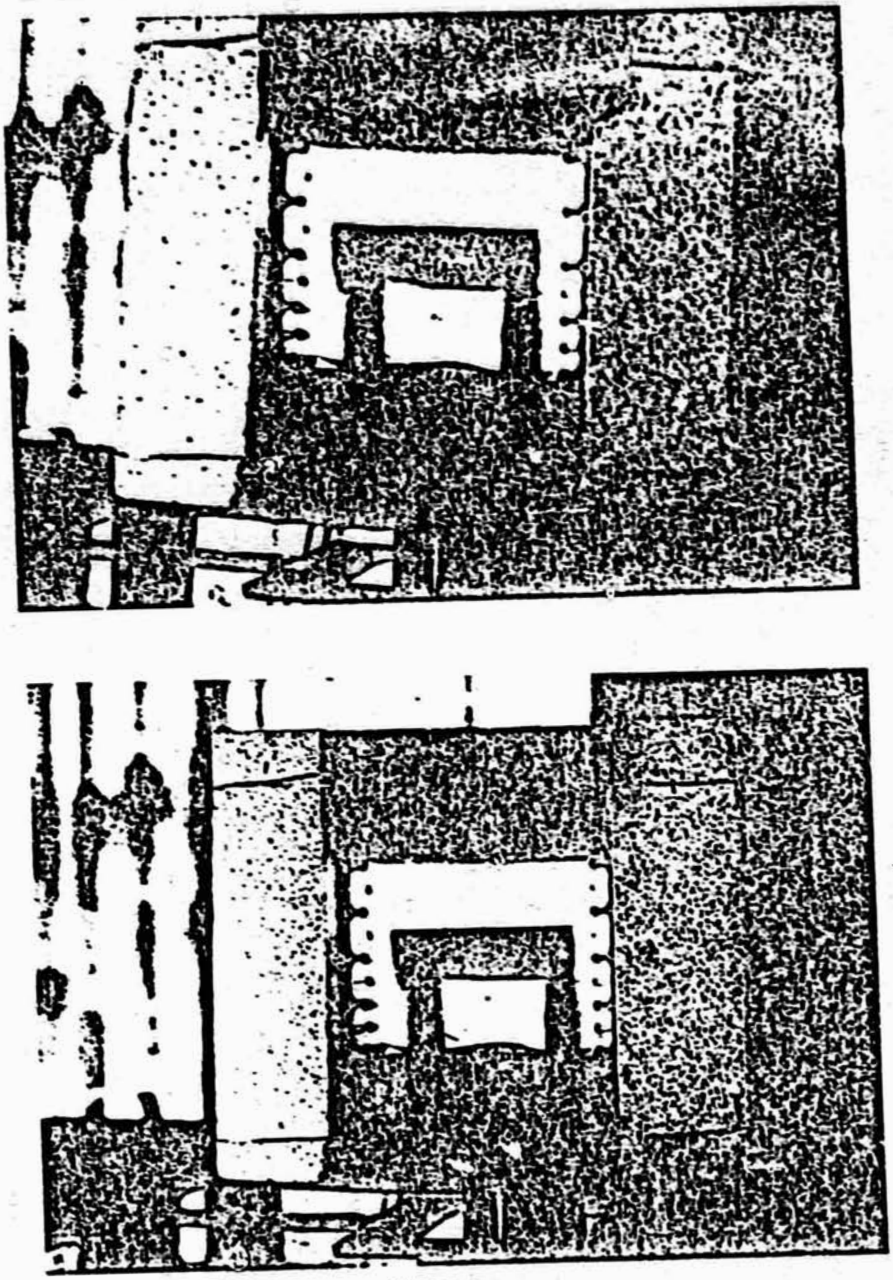


FIG. 14

Containerless Melting Of Aluminum

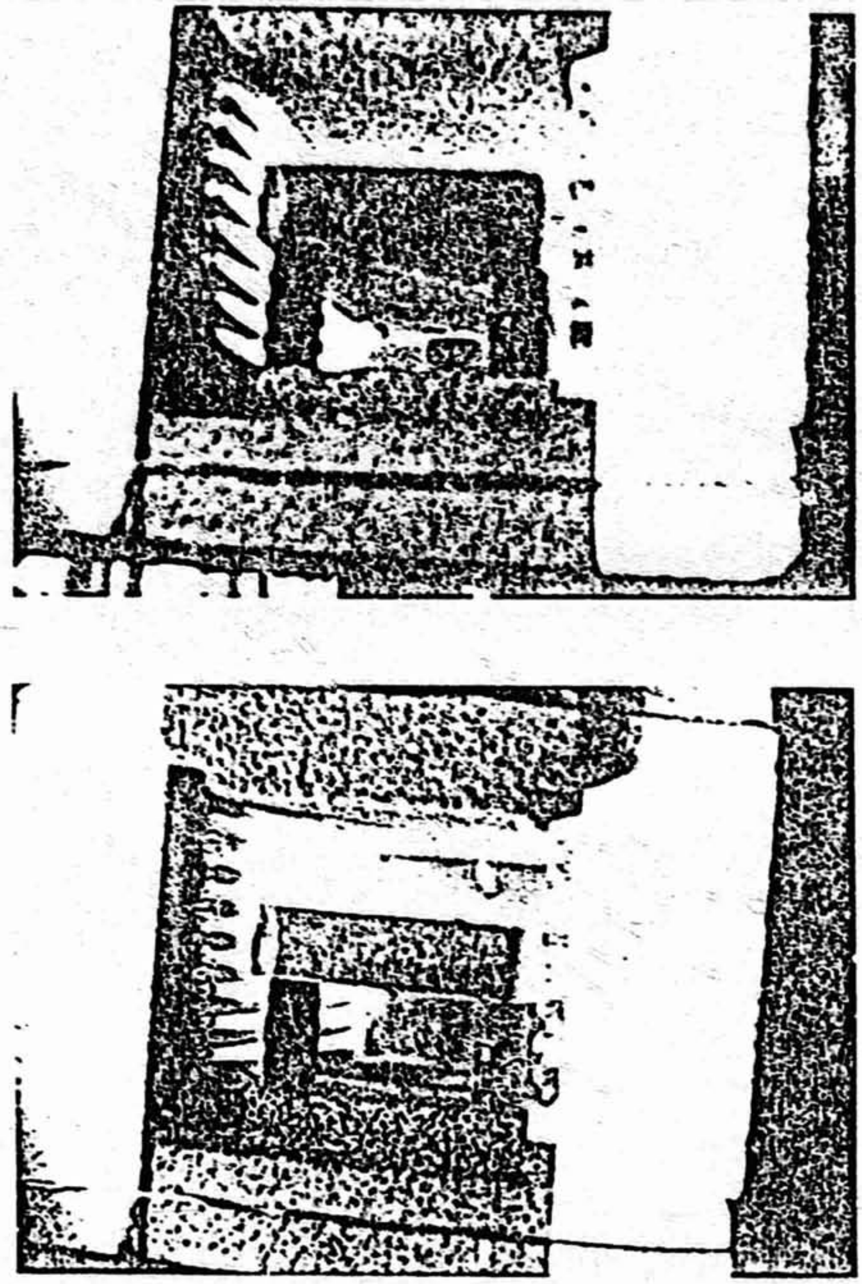


FIG. 15

Containerless Melting Of Glass

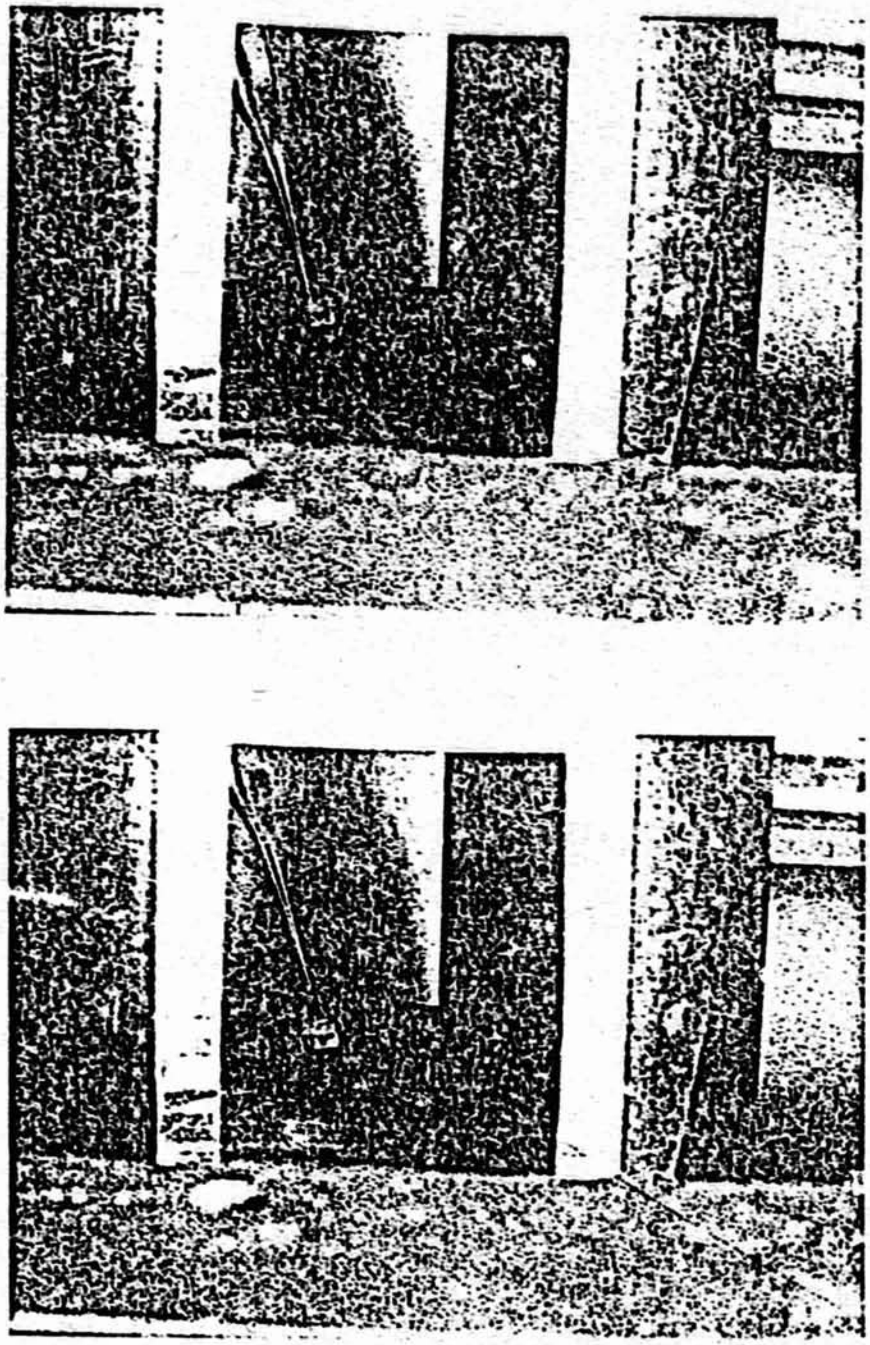


FIG. 16

Injection Of Liquids Using
Droplet Detachment Method

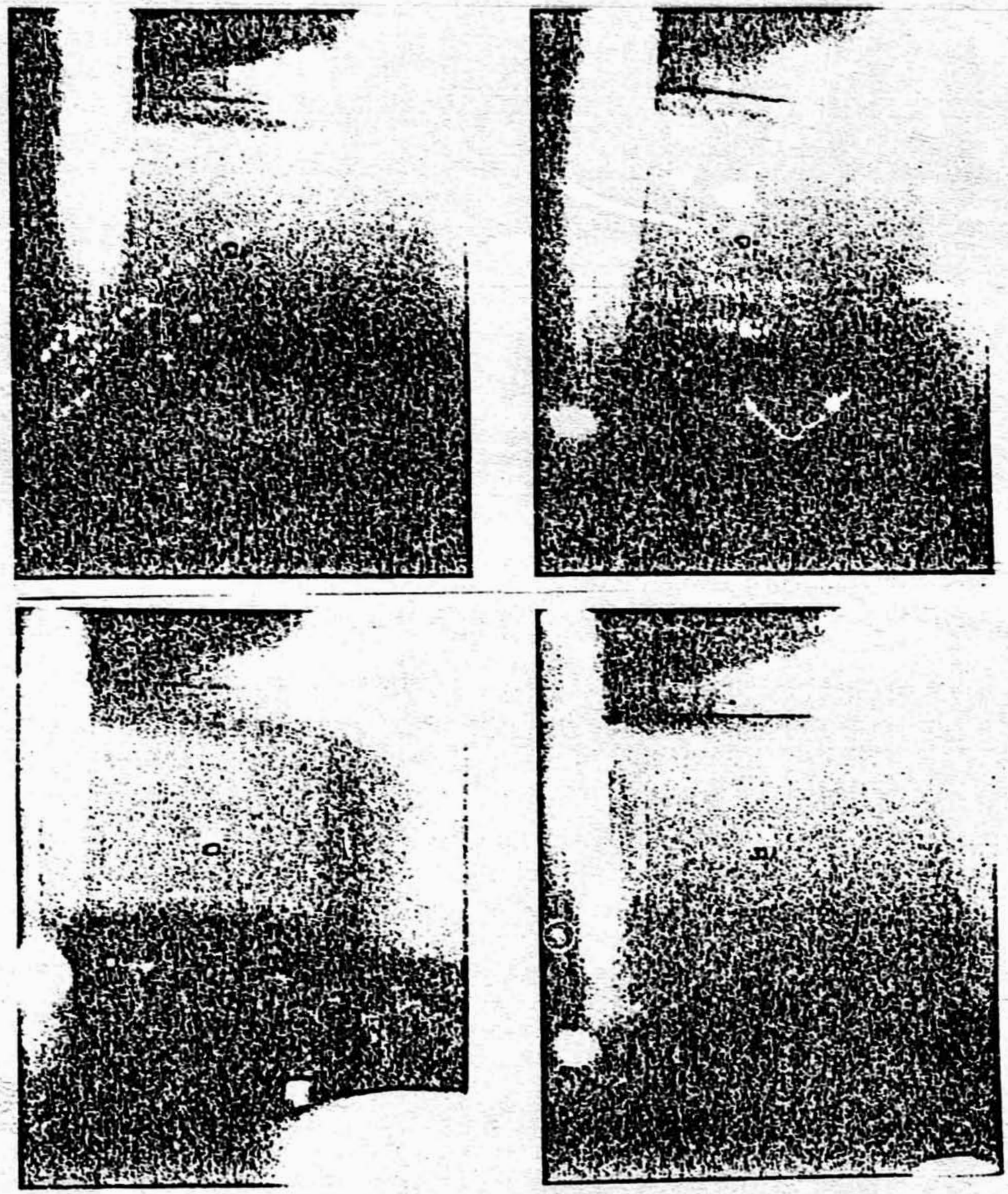


FIG. 17

Shaping Of A Water Drop By
Increasing The Sound Intensity.
Top Left Photo Was For 130db S.P.L. Total
Total Increase In S.P.L. About 6db.

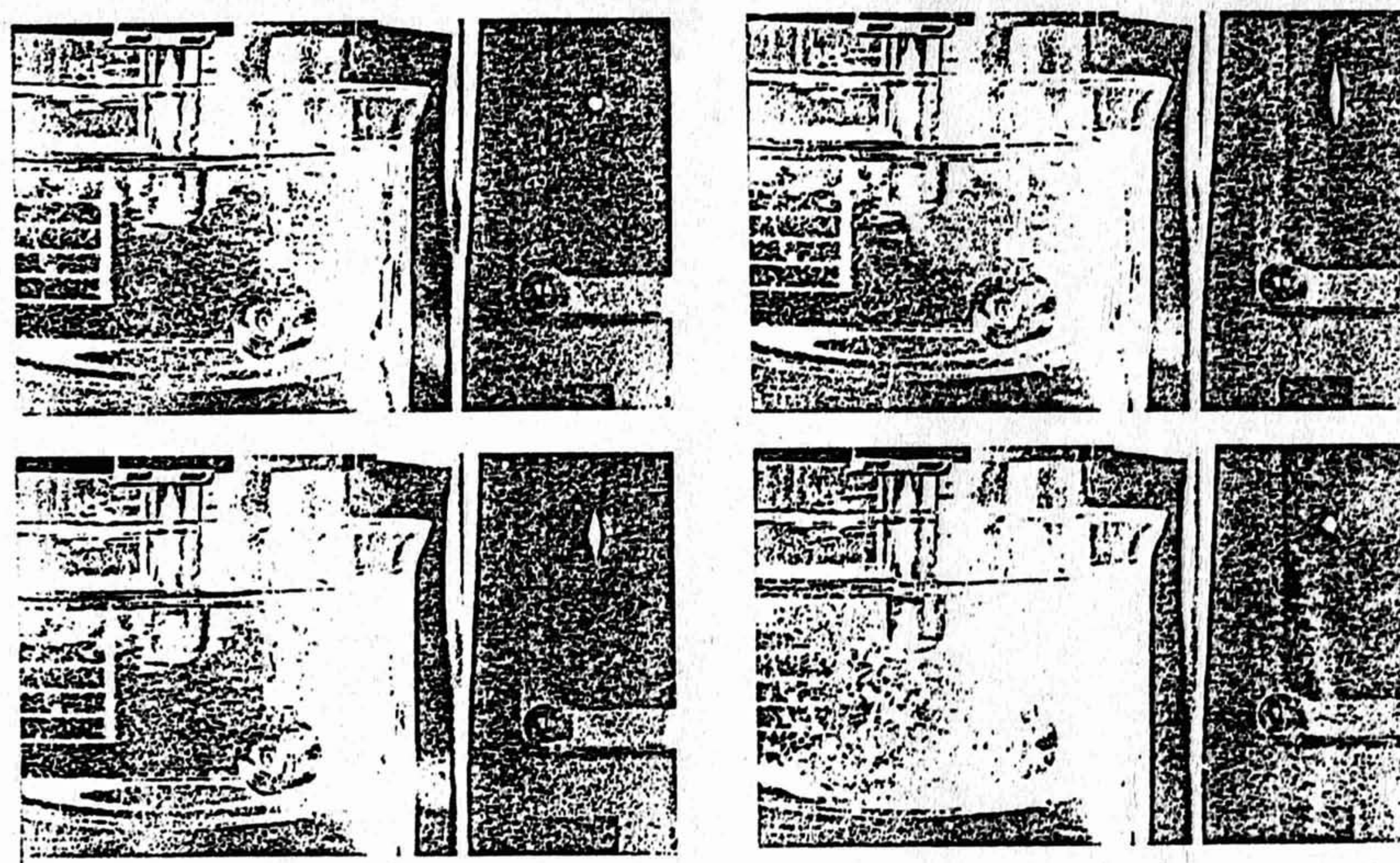
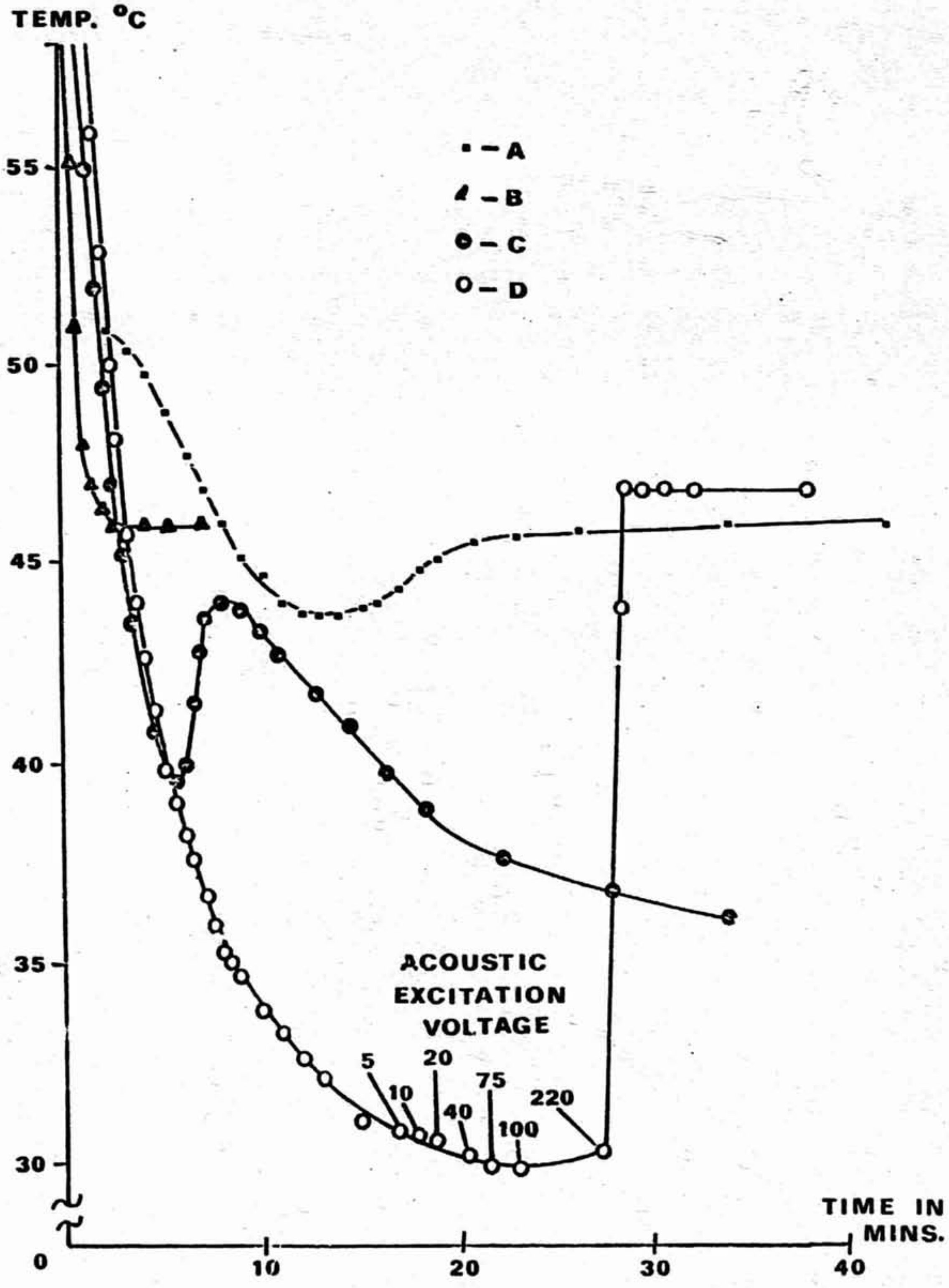


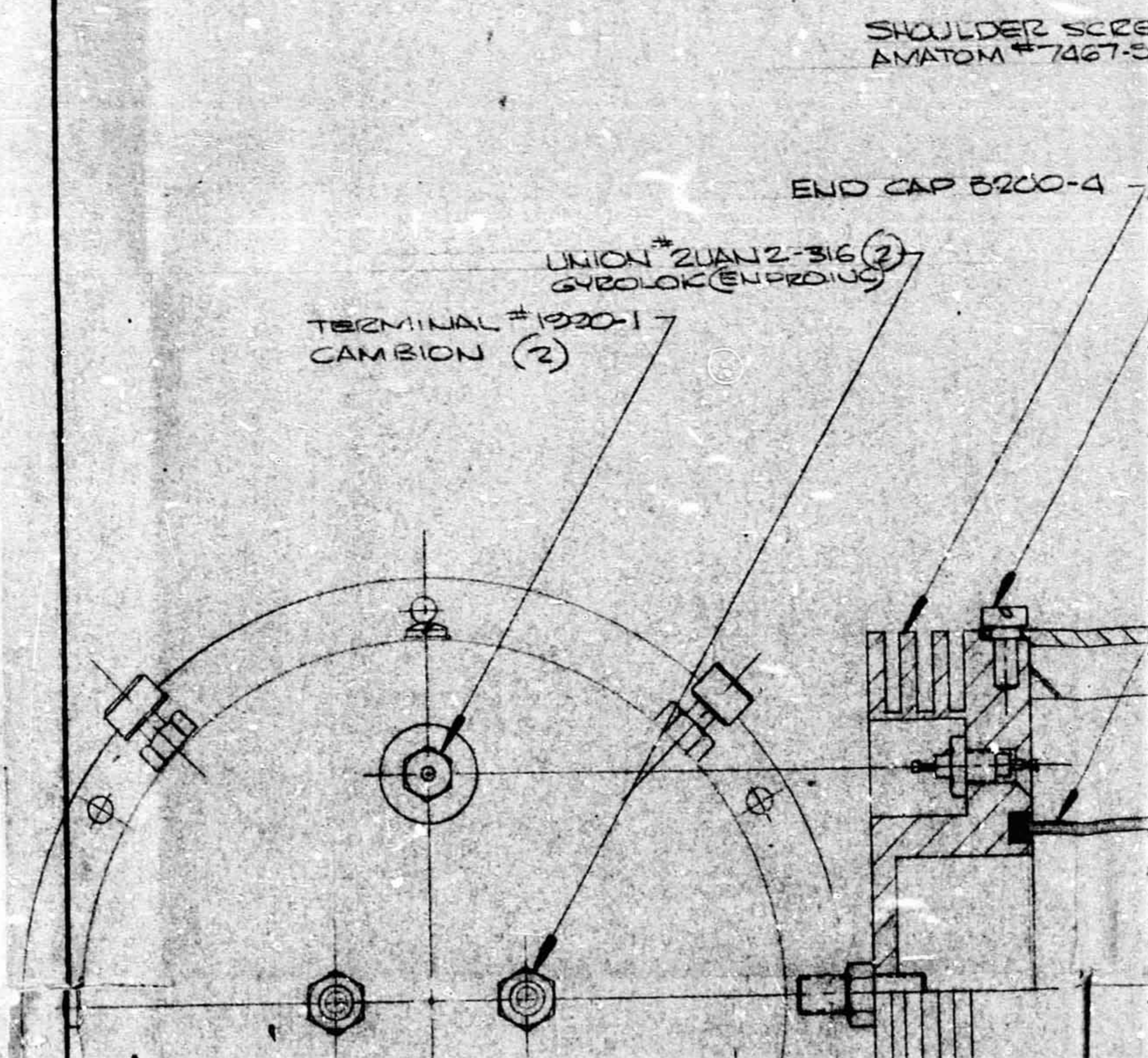
FIG. 18

Direct Acoustic Irradiation
Of Supercooled Benzophenone.
Crystallization Occurs At
The Vaporous Cavitation Level
(Bottom Right Photo)

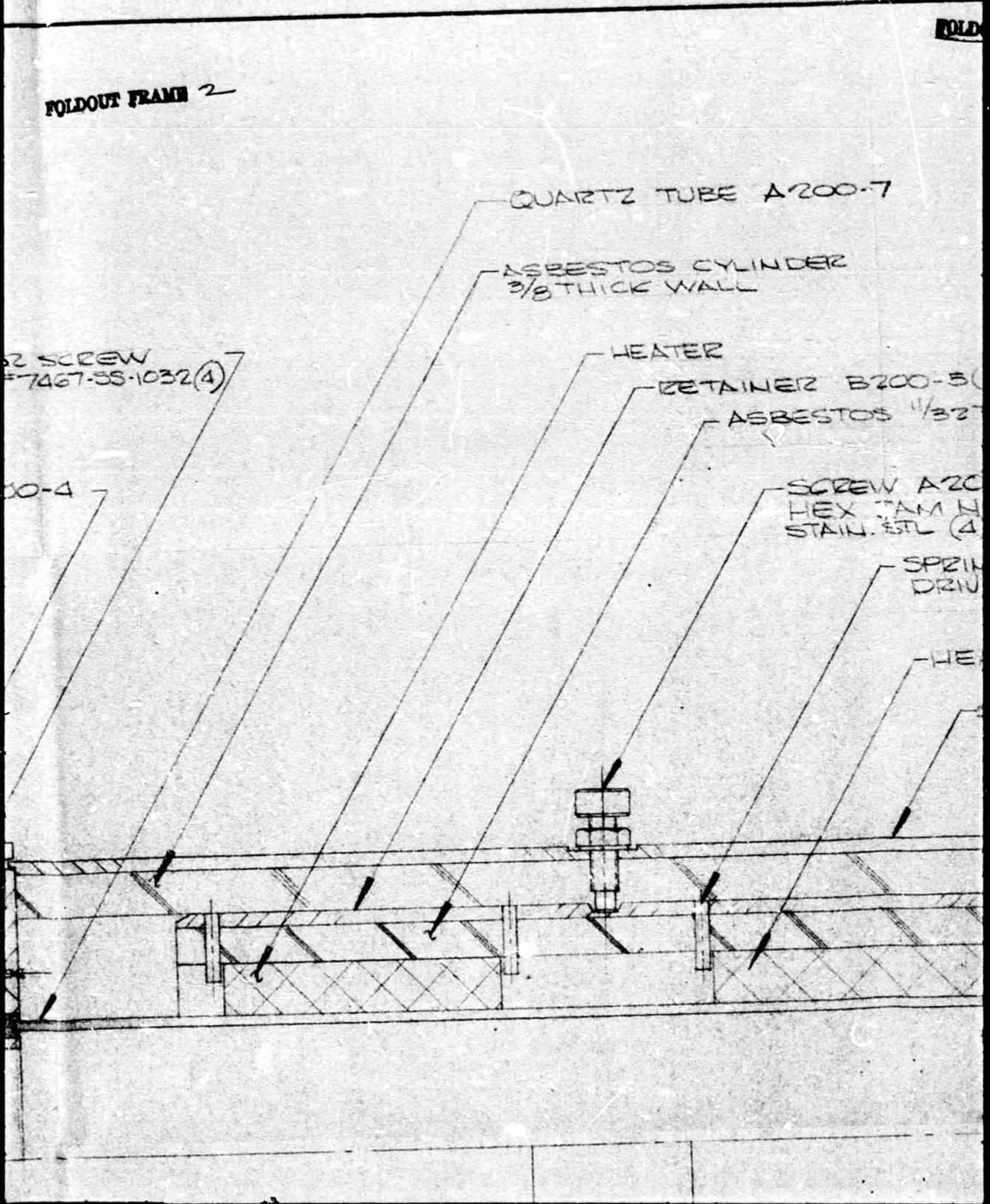


SUPERCOOLING OF BENZOPHENONE

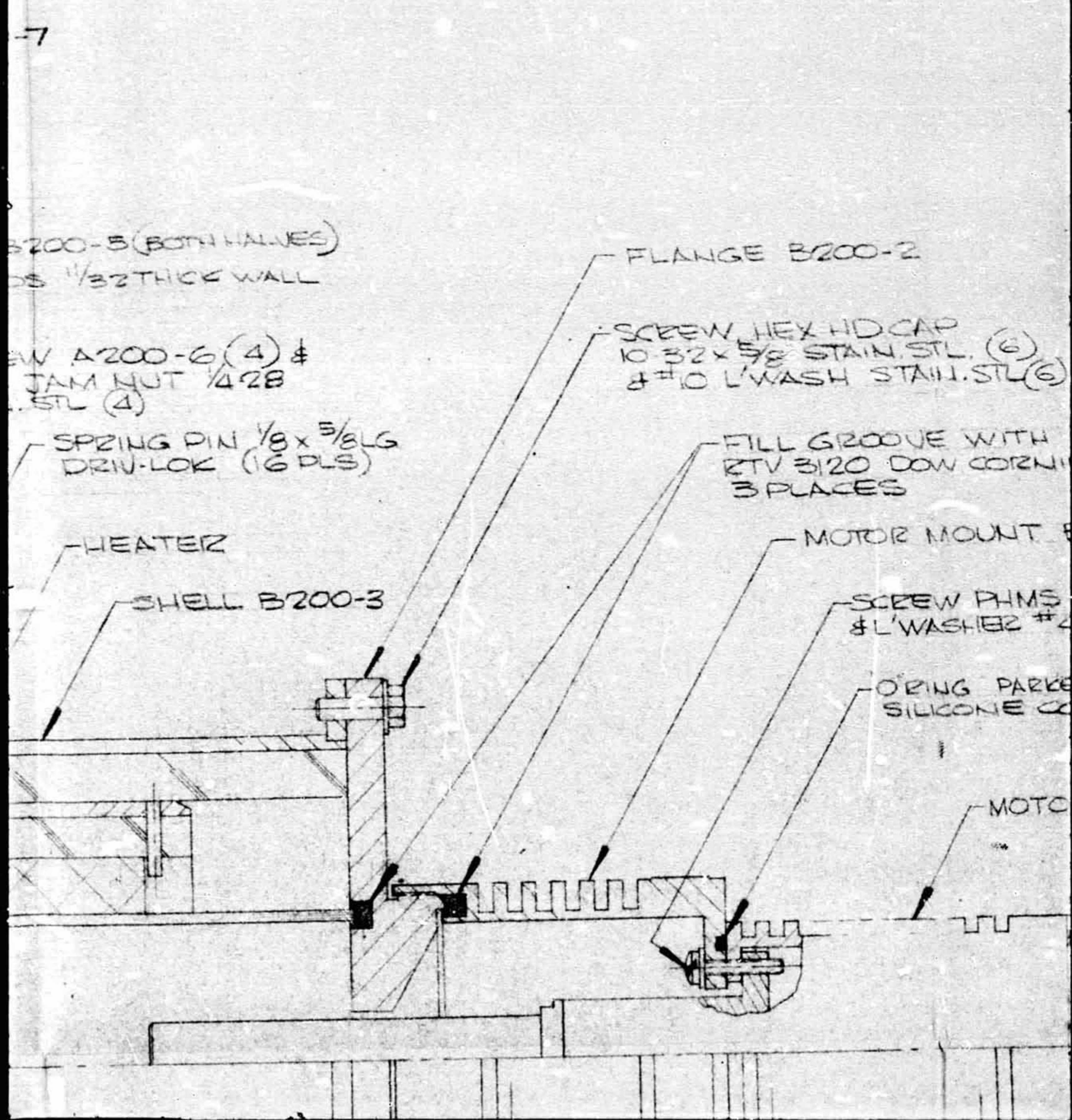
FIG. 19


SHOULDER SCRE
AMATOM #7467-5
END CAP 8200-4
UNION #2UAN2-316 (2)
GYROLOK (ENPROINC)
TERMINAL #1990-1
CAMBION (2)

FOLDOUT FRAME 2



FOLDOUT FRAME 3



A) ORIGINAL 6-10-74

OLDOUT FRAME 4

6)
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R #4 (3)

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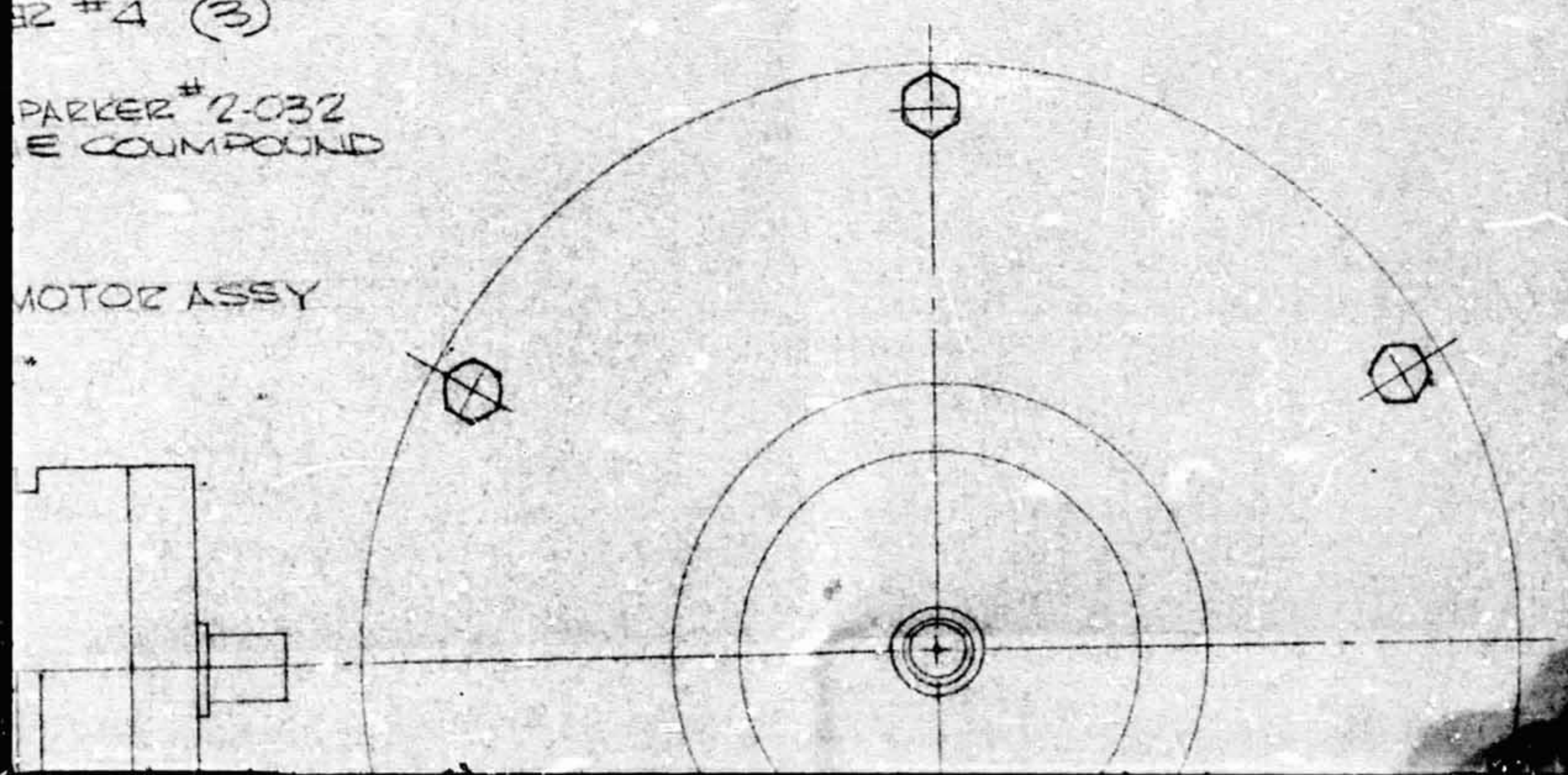
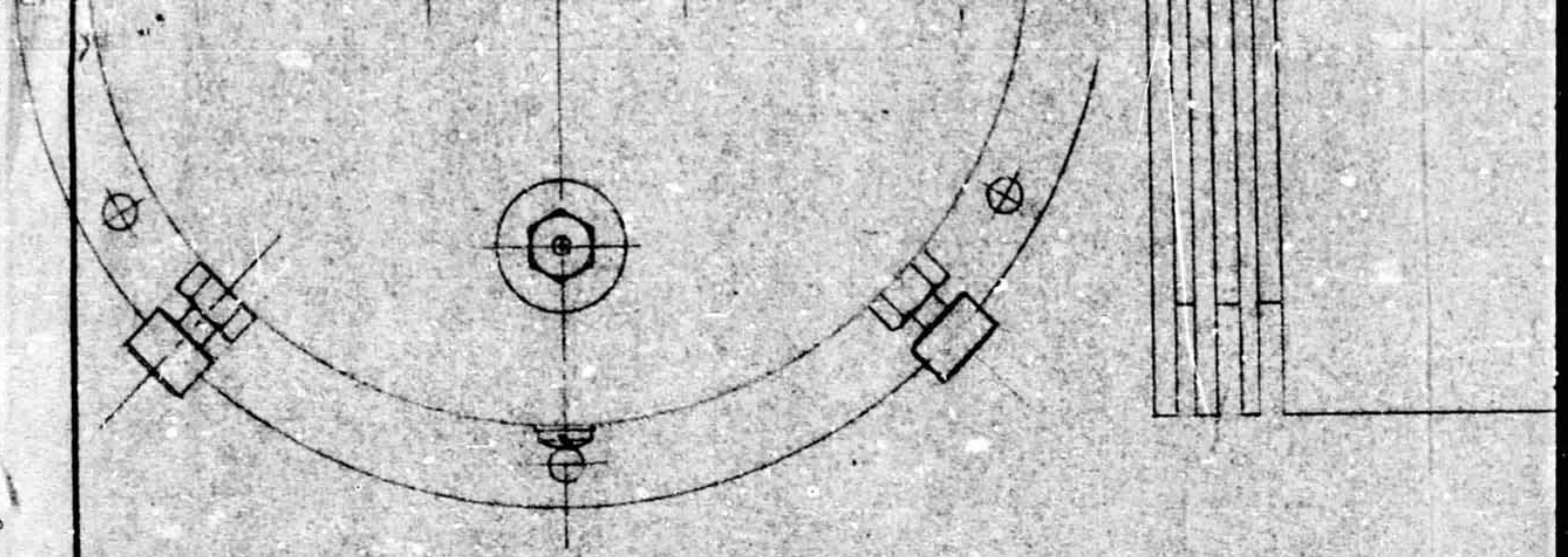
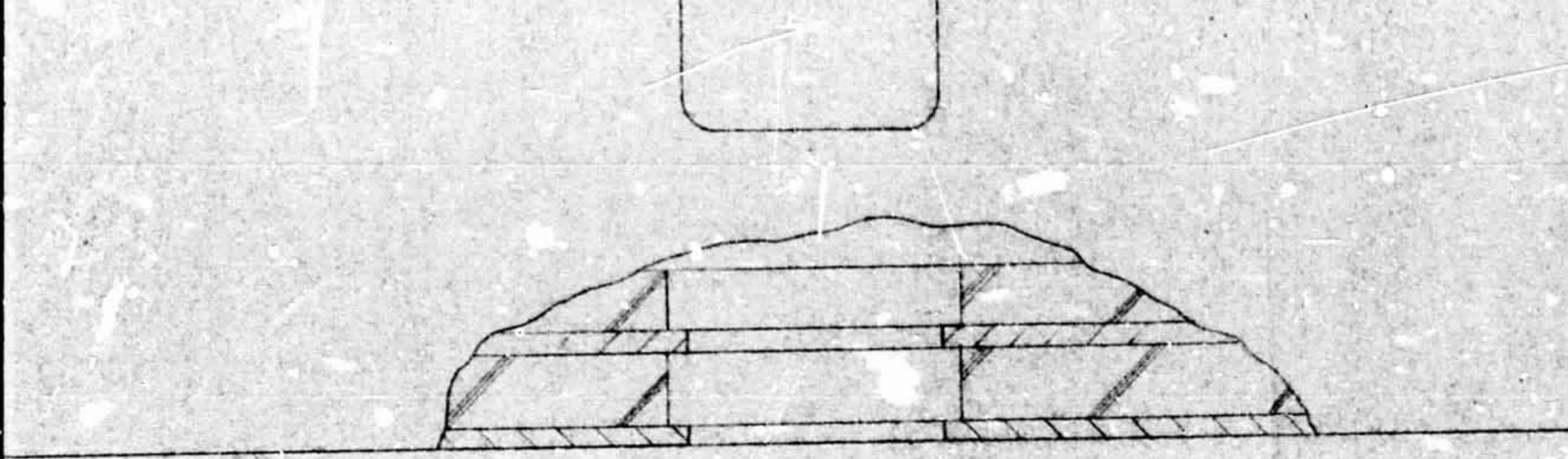




FOLDOUT FRAME 5



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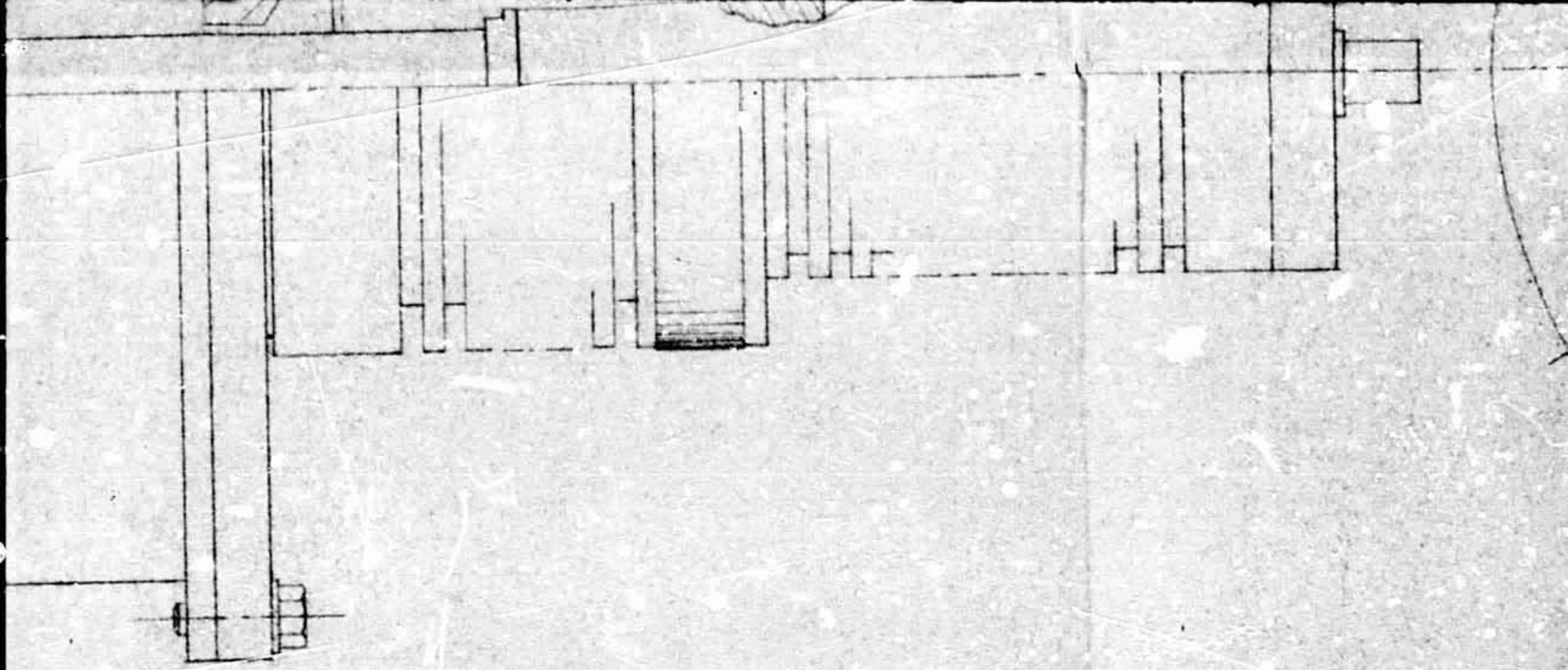
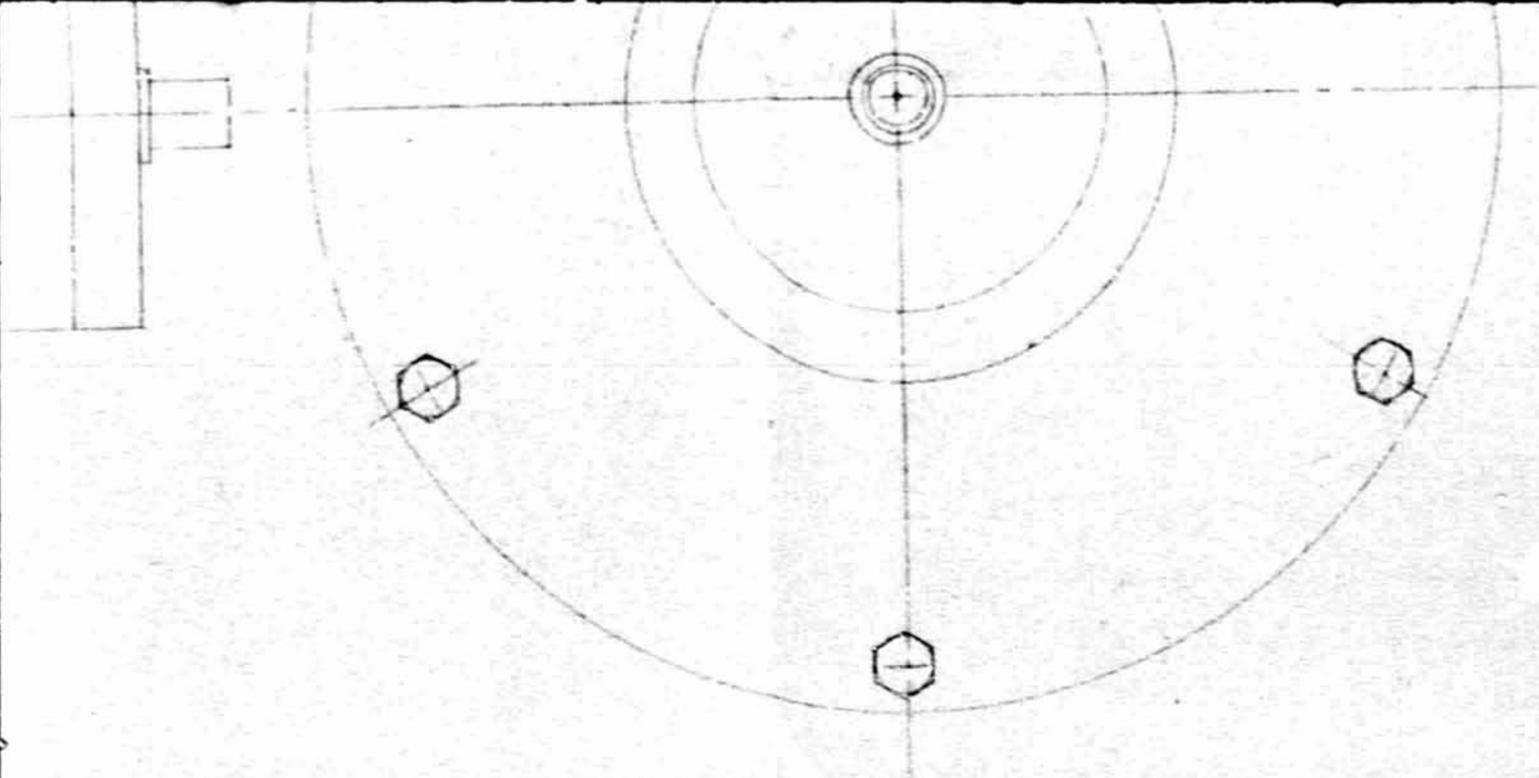


FRAME 7



FOLDOUT FRAME 8

INTERSONICS INCORPORATED

SCALE: FULL	APPROVED BY:	DRAWN BY
DATE: 6-10-74		REVISED
FURNACE LAYOUT /ASSY NAS 8-30471		
FIGURE 20		DRAWING NUMBER D 200